The effect of visual capacity and swimming ability of fish on the performance of light-based bycatch reduction devices in prawn trawls

By
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Declaration

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Statement of Co-Authorship

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Abstract

Discarding is the practice of returning unwanted catch to the sea during commercial fishing. However, the discarding process is costly and time consuming and some fish bycatch species have a high post-capture mortality rate. Therefore, reducing bycatch and thus discarding is a major reason for ongoing research and development into Bycatch Reduction Devices (BRDs). This research presents a novel BRD that uses artificial light attached to the headline of commercial prawn trawl nets and insight into its effect on reducing the overall capture of fish bycatch. Two designs of light BRDs were developed and tested in the temperate waters of North-Eastern Tasmania as well as the tropical waters of Moreton Bay, Queensland. It was found that there was a 50% reduction in total fish bycatch in temperate waters but no evidence of a significant difference in total fish catch in tropical waters. There were species-specific differences in the changes of catch rates with the use of the lights. Most species were found to decrease in catch with the use of light, and one species in particular, *P. bassensis*, was reduced by 75%. The only evidence that the lights had any effect on size distribution was found for two species, *T. declivis* and *P. melbournensis* that had significantly different length frequency distributions with the use of artificial light.

In an attempt to explain species-specific changes in catch rates, the visual and swimming capabilities of a range of bycatch species were studied. The photoreceptor cell densities and potential visual acuity were quantified using histological techniques on the eyes of eight species of interest: *Lepidotrigla mulhalli*; *Lophonectes gallus*; *Platycephalus bassensis*; *Sillago flindersi*; *Neoplatycephalus richardsoni*; *Thamnaconus degeni*; *Parequula melbournensis*; and *Trachurus declivis.* The cone densities ranged from 38 cones per 0.01 mm^2 for *S. flindersi* to 235 cones per 0.01 mm^2 for *P. melbournensis*. The rod densities ranged from 22 800 cells per 0.01 mm^2 for *L. mulhalli* to 76 634 cells per 0.01 mm^2 for *T. declivis* and potential visual acuity (based on anatomical measures) ranged from 0.08 in *L. gallus* to 0.31 in *P. melbournensis*. Higher rod densities were correlated with maximum habitat depths. *Parequula melbournensis* had the greatest potential ability for detecting fine detail based on eye anatomy. The stride length and maximum swimming speeds were estimated for five of these eight species. The maximum swimming speeds of *L. mulhalli*, *P. melbournensis*, *P. bassensis*, *T. degeni* and *T. declivis* were 1.71, 4.17, 4.80, 3.19 and 6.40 m s^{-1}, respectively. *Trachurus declivis* had the longest stride length and

fastest maximum swimming speed. Therefore, based on swimming capability it is predicted that of the five species studied, *T. declivis* would be most likely to avoid capture by a trawl net.

The results show a linear relationship between the potential visual acuity and percent change in catch rate, and also between the maximum swimming speed and percent change in catch rate of the species of interest. Maximum swimming speed explained 83 % and 88 % of the change in weight and numbers, respectively. Potential visual acuity was only able to explain 5 % and 23 % of the change in weight and numbers, respectively. When combining the two factors, they accounted for 74 % and 82 % of the change in weight and number, respectively. This study concludes that maximum swimming speed is sufficient for predicting the percent change in catch rate of a species when using artificial light. This relationship is beneficial for predicting the catch rates of different species in trawls fitted with the novel light BRD.

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Chapter 1: Introduction

1.1. Issue of discarding

For decades, the world's ocean marine resources have increasingly been utilised as a source of protein. From supplying food for populations, to multiple uses in manufacturing and industry, growing demand for fish and fish products also brings an increasing need for sustainable fishing practices (King 2007). Fish and fish products represent an important source of protein and in some countries there may be few alternatives (FAO 2014). In 2012, global production of fisheries was 91.3 million tonnes (FAO 2014). On a more local scale, in Australia exports bring over $2.5 billion dollars each year and each part of the harvest-to-market chain contributes to the economy, both locally and nationally (Patterson *et al.* 2015).

During commercial fishing practices, non-target species will be caught (DAFF 2000). This catch is divided into marketable and non-marketable species. The marketable species, called 'byproduct species', are kept because they have market value (DAFF 2000). Bycatch is defined as the part of the catch that is returned to the sea due to regulations or lack of commercial value and it is also the part of the catch that interacts with the fishing gear without reaching the deck (DAFF 2000). The practice of returning unwanted catch overboard is referred to as discarding (Elliston *et al.* 2005). Discarding bycatch is a major threat to the sustainability of commercial fisheries around the world.

In 2004, it was estimated that 7 million tonnes of commercial catch were being discarded in fisheries worldwide (Kelleher 2005; Alverson *et al.* 1994). Discarding is considered a threat to sustainability due to the uncertain nature of the post-capture and release survival (DAFF 2000; Walker *et al.* 2010). Although methods are available for estimating discard mortality rates, this type of data does not exist for many fisheries (Davis 2002). The effect of discarding can be a loss of yield i.e. with the mortality of undersized valuable commercial species that will not have the opportunity to grow and reproduce (Catchpole *et al.* 2006). There may also be an ecological impact as the spawning stock is reduced (Catchpole *et al.* 2006). Light conditions, availability of oxygen, sea conditions, air exposure and size of fish can also affect the likelihood of mortality after being returned to the sea (Davis 2002).

Over the last couple of decades, many attempts to reduce bycatch have been tried, tested and, in many cases, adopted into industry (Eayrs *et al.* 1997). Discarding bycatch has

declined worldwide in association with decreases in overall catch, the greater use of bycatch species as byproduct, an improvement in gear selectivity, reduced effort for target species with high bycatch abundance, evolving management regimes and the increasing of expertise and awareness by fisheries managers and the community (Elliston *et al.* 2005; Kelleher 2005; Zeller and Pauly 2005). The benefits of reducing bycatch range across economic, ecological and social components (DAFF 1999; King 2007; Walker *et al.* 2010). The economic productivity of fisheries can be increased with higher quality catches, shortened sorting times, and reduction in fuel consumption as well as gear damage (DAFF 1999; DAFF 2000). There are direct benefits to the stocks and flow on effects that maintain the integrity of the marine ecosystem (DAFF 1999; DAFF 2000). The benefits also flow on to the community, in particular all those involved with harvest, processing, wholesale, retail and also the consumers (Walker *et al.* 2010).

1.2. Bycatch Reduction Devices (BRDs)

There are two basic methods for facilitating bycatch reduction in BRD's; (i) devices based around the differences in behaviour between target and non-target species and (ii) barriers. Developing successful bycatch reduction devices requires an understanding of the behaviour of non-target species as they interact with the fishing gear. At any point of the trawl capture process, fish have the opportunity to avoid or be captured by the trawl net. As the trawl net encounters the fish there are certain selection processes that occur (Figure 2). Depending on the position of an individual in front of the net and within the net, the fish may be able to avoid or escape the trawl. The term "avoid" refers to the fish that keep out of the way of an oncoming net and in the context of this thesis will relate to whether or not a fish is caught.

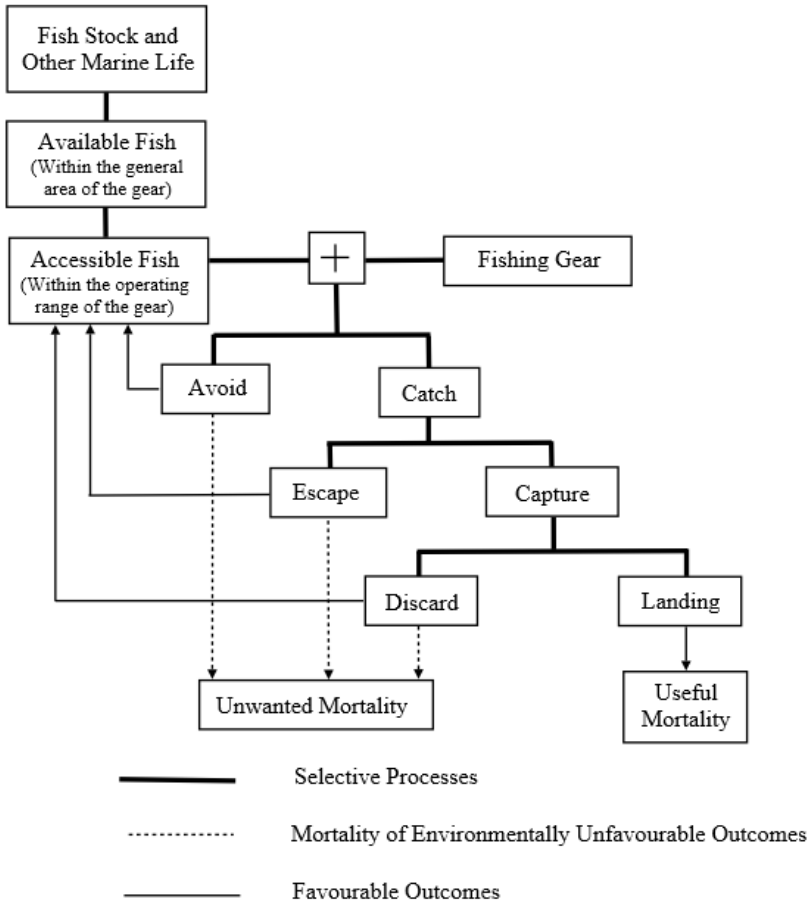

Figure 2: Selectivity in the catching process (from Dickson *et al.* 1995).

Reception, orientation and signalling in fish contribute to their behavioural reactions (Manteifel *et al.* 1971) and for many years the behaviour and physiology of fish has been manipulated to optimise the capture and culture of different species (Bardach and Magnuson 1980; Eayrs *et al.* 1997). For teleost species it depends on their swimming ability, behaviour and also their senses. For example the 'FishEye' has been developed in prawn trawls and is an opening big enough for fish to escape through that is placed in the top panel of the codend (Eayrs *et al.* 1997). They are strategically placed gaps that allows strong swimming fish to exit the codend with minimal loss of prawns (Eayrs *et al.* 1997). Secondly, BRDs can also be designed to block entry into the codend as seen with Turtle Excluder Devices (TEDs). TEDs such as the Nordmore grid and Northern Australian Fisheries TED (NAFTED) are types of bycatch reduction devices. They are made of a solid barrier that allows prawns to pass through and larger turtles, sharks and rays to be guided out of the net (Figure 1) (Eayrs *et al.* 1997).

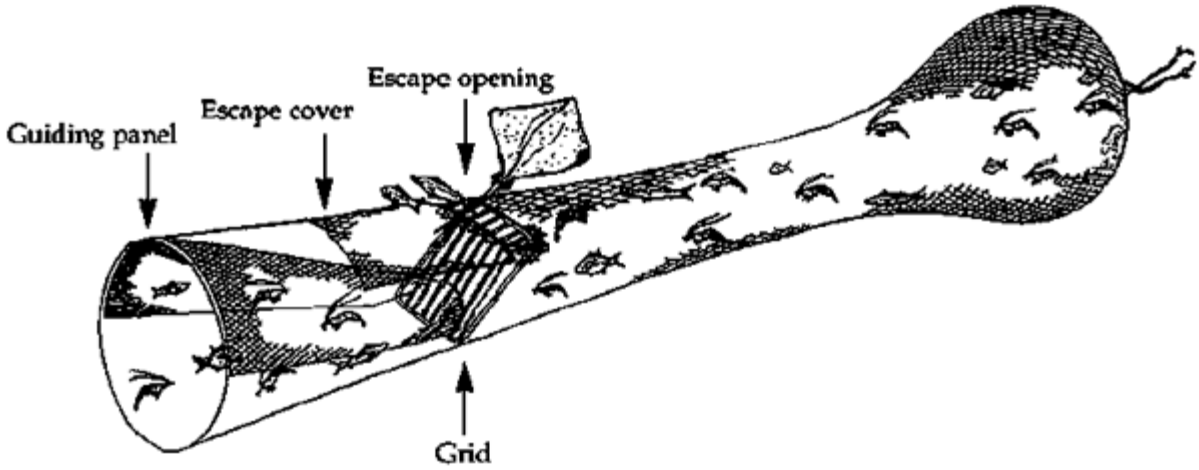

Figure 2: An example of a bycatch reduction device, the Northern Australian Fisheries TED (NAFTED) (Brewer *et al.* 1998).

A 'TED and BRDs Testing Protocol' was developed by a bycatch committee of the Northern Prawn Fishery Management Advisory Committee (NORMAC). This protocol promotes the design of new or modified devices and provides a basic outline for their assessment before they can be introduced into the fishery (SAFMC 1997). The three main stages include: an initial assessment stage that involves the committee assessing the potential based on diagrams and photographs; a visual assessment phase follows and requires a physical assessment of the constructed device; and the last step is to test the device at sea (Figure 2) (SAFMC 1997). Some of the criteria that the prototype must adhere to include reduction of bycatch, impact on target species, safety, impact on normal fishing activities, as well as cost (SAFMC 1997).

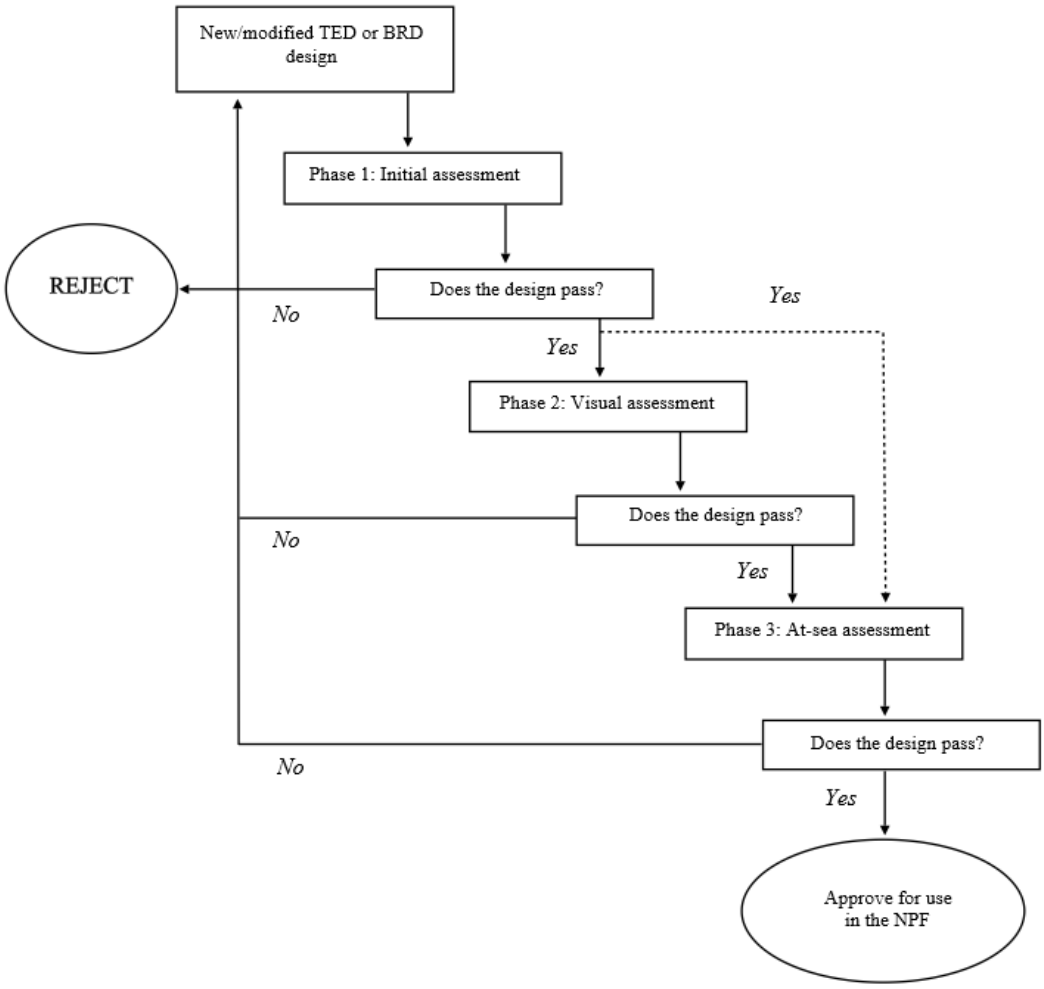

Figure 3: A framework for testing a BRD or TED (Brewer *et al.* 1998)

1.3. Prawn trawl fisheries

Globally, prawn trawl fisheries (sometimes termed "shrimp" trawl fisheries) have the highest capture of bycatch species that accounts for 27 % of the world's commercial discards (Eayrs 2007). Researchers in the United States pioneered efforts to reduce bycatch in prawn trawl fisheries. They recognised that prawn trawling was the single greatest threat to marine turtles that had just been recognised as threatened or endangered species (Kennelly 2007). This lead to an investigation into methods for mitigation of their capture including; closures, restricted tow times and gear modifications (Kennelly 2007). It was in 1980 that the turtle excluder device (TED) was first designed and nine years later that the mandatory use of these devices came into effect (Kennelly 2007). Over the years many other bycatch reduction devices have been trialled by fishers, gear technicians and

biologists in an attempt to reduce unnecessary mortalities of non-target species (Watson *et al.* 1999).

Mexico has four main prawn fleets operating on the Pacific coast and in the Gulf of Mexico and has also conducted studies on the bycatch species being caught (Gillett 2008). Grande-Vidal and Diaz (1981) concluded that the proportion of fish to prawns was 9:1 on the Pacific coast and 3:1 in the Gulf of Mexico (Gillett 2008). Prawn trawlers have been required to use a TED since 1993 in the Gulf of Mexico and 1996 on the Pacific coast. Aside from TEDs, other BRDs such as the 'FishEye' are also in use (Eayrs 2007). In Southeast Asia over the last two decades, the Southeast Asian Fisheries Development Centre (SEAFDEC) has been conducting ongoing projects. This intergovernmental organisation developed a Juvenile and Trash Excluder Device (JTED) that was successfully tested in several Southeast Asian countries (Eayrs 2007). Another design, called the Thai Turtle Free Device (TTFD) was also successfully developed between Thailand and SEAFDEC. In countries such as Thailand, Indonesia, Malaysia and the Philippines, BRDs have now become compulsory (Eayrs 2007).

In 2000, bycatch rates in the Arabian Gulf were high, for example in Kuwait the ratio of bycatch to prawns was 74:1 (Al-Baz & Chen 2015). As a result of this, various modifications such as TEDs, fisheyes and square mesh codends have been tested and developed (Al-Baz & Chen 2015). Similarly, in Iran testing of BRDs has been ongoing and includes the use of the Northern Australian Fisheries TED (NAFTED) (Eayrs 2007).

The Northern Prawn Fishery (NPF) is one of Australia's most valuable fisheries with a gross value of $88.8M in 2010 (Woodhams *et al.* 2011). There are currently 52 vessels operating from March to June when targeting banana prawns (*Fenneropenaeus indicus* and *F. merguiensis*) and August to November for tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) (Woodhams *et al.* 2011). Daytime trawling is banned when targeting tiger prawns to protect the mature females and thus protect the breeding stock (Woodhams *et al.* 2011). These species are the target species that are exported to Japan and sold in the Australian domestic market (Woodhams *et al.* 2011). The capture of bycatch in Australian prawn fisheries have been a major concern as they are recognised to be one of the least selective forms of fishing (AFMA 2009). The NPF interacts with a range of species including turtles, sea snakes, sharks, rays and sawfish as well as hundreds of species of fish and invertebrates (AFMA 2009). In 2001, BRDs and TEDs became mandatory which

halved the prawn to bycatch ratio (Woodhams *et al.* 2011). This means, (based on 2010 tiger prawn catches) 16 000 tonnes of bycatch would be caught annually in unmodified nets but with the use of BRDs, fishers actually only catch around 8 000 tonnes.

The most common BRDs and TEDs that are used in the NPF include the Nordmore grid, FishEye, square mesh window, radial escape section and NAFTED (Eayrs *et al.* 1997; Salini *et al.* 2000) but there are others. Nets can also be modified in other ways to reduce bycatch such as using a square mesh codend, reducing the headline height, spreading and altering the ground gear. The grids (TEDs) are very effective at excluding large bycatch species such as sharks, turtles and rays while the BRDs, fisheyes and square mesh windows, help reduce the fish species by up to 39% (Brewer *et al.* 1998).

1.4. The use of light in fisheries

BRDs are created because prawn trawls are designed to prevent fish escaping once they have encountered the net. BRDs are usually designed to allow bycatch species to escape through the codend. Currently there are few designs that prevent unwanted bycatch species from entering the net in the first place; these include covering the mouth of the trawl with mesh, or reducing the headline height (Eayrs *et al.* 1997). A new concept is now being developed that uses artificial light placed at the mouth of the trawl to illicit a negative phototactic response from teleost species.

This concept was first tested by Clarke and Pascoe (1985) who used electric light in the capture of deepsea animals. This study used one 70 watt divers' light attached to the headline of a net taken to depths of up to 1800 meters. They found that the total volume of fish increased by up to 79 %. The next study was conducted the very next year, in depths of 55 to 67 meters off the coast of Plymouth, UK. With the addition of two of these 70 watt divers' lights on the trawl net, it was found that there was no change on overall capture of fish during the day and night (Clarke *et al.* 1986). In more recent years, the concept was reinvigorated by researchers from the Australian Maritime College in 2008 when artificial light was used to reduce bycatch in the Torres Strait prawn fishery. A set of 8 lights was rigged to two of the nets on a quad rig prawn trawl vessel in the Torres Strait Prawn Fishery (Gaston 2008). This same set of lights was used two years later in a similar study conducted in the Northern Prawn Fishery (Maynard and Gaston 2010). In the latter

study, the lights were successful in reducing the number of bycatch fish and mobile invertebrates by up to 50 %. The most recent study to use this technology was conducted in the Oregon prawn trawl fishery in the United States. It was found that there were major reductions in the catch of the bycatch species that were studied (Hannah *et al.* 2015). For example, echelon (*Thaleichthys pacificus*), a threatened anadromous smelt, was reduced by 91 %. The testing of this light system was so successful that the device has had rapid and broad uptake into the industry.

This novel concept is thought to work due to the light scaring the fish away before encountering the net, or illuminating the area in front of the net and thus allowing fish to make an orderly escape (Glass and Wardle 1989; Hargreaves and Herring 1992; Walsh and Hickey 1993). Although it is widely recognised that stationary light will often attract fish due to the congregation of microscopic zooplankton (Ben-Yami 1976), moving light provokes an entirely different response. Static light attracts plankton in the water which is food for species of fish (Kehayias *et al.* 2008). This is classically used in fisheries such as squid fishing, where the light is suspended above the boat, attracting the squid, which are then caught with jigs (Ben-Yami 1976). The lines are lowered between 30 and 100 m, depending on the power of the lights and subsequent depth of penetration, and jigged up and down (Ben-Yami 1976).

It has been found that in darkness, an individual fish that has encountered parts of the trawl gear will respond in an unordered fashion (Blaxter and Batty 1987; Glass and Wardle 1989; Ryer and Barnett 2006). An ordered reaction, often termed ‘running’, is a reaction that usually occurs in the presence of light. It is therefore known that the visual capacity of the species plays an important role in the ability to detect the oncoming trawl. The ability for the species to avoid the trawl will be determined by the swimming capabilities of the species.

1.5. Ability for teleost species to detect trawls

Fish have a light intensity threshold; below this they are unable to detect the trawl until it is upon them (Glass and Wardle 1989). Above this they are able to detect the gear and form ordered responses. However, if the light is adequate to provoke an ordered response before encountering the sweeps, then avoidance is more likely. It has been shown that

increases in the distance at which the fish detects the net increases the likelihood of escape (Hargreaves and Herring 1992; Walsh and Hickey 1993; Zhang and Arimoto 1993). Factors affecting this include ambient intensity of light, turbidity of the water and visibility/contrast of the gear (Cui *et al.* 1991; Douglas and Djamgoz 1990a) but also the potential visual acuity of the species (Hajar *et al.* 2008; Wardle 1993; Zhang and Arimoto 1993).

Just like other vertebrates, most teleost species use photoreceptor cells to detect colour and bright light (cones) and dim light (rods) (Fernald 1990). The different densities, form and arrangement of these cells are a function of their adaption to certain environments and life histories. It has been found that the densities of these photoreceptor cells vary with age or size of the fish (Douglas and Hawryshyn 1990b; Fishelson *et al.* 2004; Hajar *et al.* 2008; Mas-Riera 1991; Renee Lara 2001); depth (Boehlert 1978; Mas-Riera 1991); as well as behaviour and rhythmic activities (Pankhurst 1989; Renee Lara 2001). In fact, even just observing eye size is a useful tool in establishing certain behaviours of a species. Pankhurst (1989) found that herbivores were more likely to have smaller eyes and carnivores to have larger eyes. Since large eyes are associated with higher acuity it can then be surmised that the eyes of carnivores are more likely to have higher resolution (Fernald 1985). When exposed to high levels of light, cones are usually extended and rods retract (Wagner 1990). This means that individual species also have a light intensity threshold, below which scotopic vision is used and the ability to resolve images is reduced (Miyazaki *et al.* 2000).

Potential visual acuity (also known as spatial resolution) is the ability for a species to detect fine detail underwater (Douglas and Hawryshyn 1990b). In its simplest form, it is described as the Minimum Separable Angle (MSA) by which the individual can distinguish two adjacent objects (Douglas and Hawryshyn 1990b). To calculate this, the lens diameter and highest density of cones (per 0.01 mm^2) are used in the following equation:

$$\alpha = \frac{1}{F}\left[\frac{0.1(1+S)\times 2}{\sqrt{n}}\right]$$

Where α is MSA (in radians), F is the lens focal length which can be calculated as 2.55 x the lens radius as Matthienssen's ratio, S is the shrinkage factor and n is the sample size.

When the MSA is found it can be used to calculate the potential visual acuity which is its inverse:

$$VA = \left(\alpha \times \frac{180}{\pi} \times 60\right)^{-1}$$

The common histological technique for observing photoreceptor cells is outlined in Ali and Anctil (1976) and adaptions of this method have been used in more recent studies (Fishelson *et al.* 2004; Mas-Riera 1991; Miyazaki *et al.* 2000; Renee Lara 2001). The use of Bouin's solution, glutaraldehyde, or osmium for tissue fixation appears to depend on the preference of the user and conditions of sample collection. The measurement of the eyeball and lens prior to fixation is crucial to determine the shrinkage factor although some studies appear to omit this step completely. Also, the orientation of eye must be considered due to the variable nature of photoreceptor cell density across the retina between species. The maximum abundance of either rods or cones is usually chosen for comparison however the location of such point much first be identified, i.e. the fovea (Wagner 1990).

Very few studies have been conducted relating the visual capabilities of fish species in response to fishing gear (Hajar *et al.* 2008; Zhang and Arimoto 1993). However, these studies introduce the concept of maximum sighting distance as a way of establishing the distance (m) at which an individual can distinguish detail of an object (Zhang and Arimoto 1993). Hajar et al (2008) found that for a target as small as the twine of a gill net, the maximum sighting distance was about 1 meter and did not change across various sized individuals. Zhang and Arimoto (1993) found an estimate for maximum sighting distance based on the target size which could be challenging to generalise if the target is a trawl net. In the end they deduced that line acuity and grating resolution maybe be more appropriate methods for describing the sighting of such objects as a trawl.

1.6. Ability for fish to avoid a trawl

The ability for an individual to avoid or escape a trawl can be influenced by the swimming ability of the individual as it encounters the gear. Swimming ability has been attributed to various types of swimming. Sustained swimming is a speed maintained for longer than 200

mins and is measured by endurance experiments, prolonged swimming encapsulates speeds that can be sustained for between 20-200 mins and is measured with critical speed, and lastly burst speeds occur for only a few seconds (Beamish 1978). Burst speed has been quantified for species in numerous studies and is more appropriate for describing the response of fish to moving fishing gear. The burst swimming speed and maximum swimming speed are often considered one and the same, however with the two different methodologies will come two different results. Theoretical models exist to describe maximum swimming speed based on the morphology of the fish such as that from Wardle (1975):

$$U_{max} = \frac{(S_L|l)}{2t_m}$$

Where U_{max} is maximum swimming speed (m sec^{-1}), S_L is the stride length (usually 0.6-0.8 times the fish length (Bainbridge 1958a)), l is the total length of the fish (m), t_m is the minimum muscle contraction time (in seconds). A direct method of observation of burst speed can be found by using a high speed camera to measure the distance covered by an individual when stimulated (He 1993; Özbilgin *et al.* 2011; Videler 1993; Wardle *et al.* 1989). While an individual may not demonstrate its maximum swimming speed when stimulated in a tank, it is more likely to respond with maximum speed if encountering a moving trawl. The ability to avoid the net also depends on the individual's ability to escape which is based on the maximum swimming speed (or burst speed) (He 1993; Yanase *et al.* 2007). This speed varies with water temperature (Videler and Wardle 1991), and also individual size as it is dependent on the amplitude of one tail beat (Beamish 1978).

Only one study has quantified these two factors, visual capacity and swimming ability, together and used them to predict the possible limit of escape distance for walleye pollock (Zhang and Arimoto 1993). The maximum sighting distance was calculated from histological examination of the eye and compared with the possible limit of escape distance calculated from maximum speed. Zhang and Arimoto (1993) acknowledge that maximum sighting distance may be better derived from line acuity or grating resolution. It was suggested that further research is required to quantify the complex visual stimuli in fish and the fish response to gear (Zhang and Arimoto 1993).

1.7. Aims of Research

This thesis aims to test the effectiveness of artifical light as a prototype light design (design details outlined in Chapter 2) that will deter a variety of species and lower the overall level of bycatch in a prawn trawl fishery. Potentially, successful use of this concept can contribute to reductions in bycatch and increase target prawn catch in Australian commercial fisheries. This will have benefits not only for the environment but also economically for the fishers. With examination of the visual and swimming ability of teleost bycatch species, this project aims to define the relationship between these factors and change in catch rates during trawling in the presence of artificial light and measured as bycatch (species, number and size distribution). The conclusions from these studies will describe how effective using light is as a BRD tool. Also, this project aims to describe the characteristics of fish physiology (visual and swimming capacity) that contribute to whether or not a species will be retained by a trawl net.

Aim 1- *To test the effect of artificial light on standardised trawl catches and on species composition.*

The greater the visual "warning", the more likely it is for an individual to avoid the oncoming net. When targeting tiger prawns during the night, prawn trawlers using artificial light could elicit a negative phototactic response well ahead of the net and increase the probability of bycatch species avoiding the net altogether.

Potential questions include:

-Does increasing the visual warning of an approaching trawl reduce overall bycatch?

-What is the effect of lights on individual species catch and size composition?

Aim 2- *To investigate the physiology of the eye of eight teleost species.*

The ability of fish to detect light relates to the presence of rods and cones (photoreceptors) and the ability to form an image of the illuminated gear will depend on their potential visual acuity.

Potential questions include:

-Does the ratio of rods to cones change according to fish species' habitat depth?

-How do the potential visual acuity and rod/cone densities change with morphologically different species?

Aim 3- *To investigate the maximum swimming ability of eight teleost species*

The ability for the fish to avoid the gear depends on its swimming ability. This is defined as the maximum (or burst) swimming speed, and inter alia is a function of individual length.

Potential questions include:

-How does maximum swimming speed change with different species (i.e. different body physiology/morphology)?

-Can we predict maximum swimming speed based on fish morphometrics?

Aim 4- *To find the relationship between the catch rates of a species in a trawl with lights and potential visual acuity and also maximum swimming speed.*

The visual and swimming capability of fish are factors that influence the difference in catch observed with the use of the light BRD.

Potential questions include:

-How do these two factors correlate to the change in catch?

-Which has a greater influence- potential visual acuity or maximum swimming speed?

-Can these variables, and their correlation with catch rate, be used to predict the potential change of catch for other species encountering a light BRD?

1.8. Ethics

Work was conducted with approval from the University of Tasmania Animal Ethics Committee, approval numbers A12574, complying with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes – 8th edition, 2013.

1.9. Outline of thesis

This thesis is written in manuscript style, with each chapter containing its own reference list and appendix, and therefore there may be some repetition.

This thesis consists of this general introduction, five research chapters and a general conclusion. It has been structured to allow the reader to first see the effect of light on fish bycatch in a tropical prawn trawl fishery and then presents the physiological factors that influence the species catch rates. In Chapter 2, the effect of light in a commercial prawn trawl fishery operating in Moreton Bay, Queensland was investigated. Next, in Chapter 3, the effect on light on eight commonly caught teleost species will be observed in the more accessible waters of North-Eastern Tasmania. This approach was taken so that these species could be studied with multiple cruises using a University vessel (RTV *Bluefin*) without any interruption to commercial fishing practices. Experiments to investigate maximum swimming speed and potential visual acuity are then conducted on these same eight species so that these two factors can be used as potential "tools" to predict the changes in catch. Chapters 4 and 5, therefore, are biological studies looking at the visual and swimming capabilities of the same eight species of fish commonly found in North-Eastern Tasmania. Chapter 4 details the photoreceptor cell densities, potential visual acuity, cone mosaics and general eye dimensions and Chapter 5 investigates the movement and maximum swimming speeds of these fish. The last research chapter, Chapter 6, brings the results of Chapters 2, 3 and 4 together by using the visual and swimming capability as a predictor of the change in catch when using light, on the eight species in North-Eastern Tasmania. The final chapter is the general conclusion, which summarises and concludes on the findings of the thesis and details possible future work.

*The author would like to note that an article based on Chapter 4 was published: Hunt, D.E., Rawlinson, N.J.F., Thomas, G.A., Cobcroft, J.M. (2015), *Investigating photoreceptor densities, potential visual acuity, and cone mosaics of shallow water, temperate fish species*, Vision Research. Vol 111A: 13-21.

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CHAPTER 2: Trials of a light emitting BRD in the Moreton Bay prawn trawl fishery

2.1. Introduction

Many different methods have been proposed to reduce bycatch, with most focussed on allowing the bycatch species to escape from the net once they have entered. In contrast the least common way of minimising bycatch is by preventing the fish from entering the net in the first place. Over the last 15 years, some work has been carried out on the use of lights to prevent fish from entering trawl nets. It has been proposed that this works either by the light scaring the fish away before encountering the net or by illuminating the area in front of the net and thus allowing fish to make an escape (Glass and Wardle 1989; Hargreaves and Herring 1992; Walsh and Hickey 1993). This concept has had mixed results when tested in the Celtic Sea (Clarke and Pascoe 1985; Clarke *et al.* 1986) and off the west coast of the United States of America (Hannah *et al.* 2015). In a study done concurrently to this one, Hannah *et al.* (2015) found that the most vulnerable bycatch species was reduced by up to 91 % which has lead to it's uptake into industry.

Although the concept of using a light BRD has been successfully trialled in the United States, in Australian fisheries it is still very novel. As such, the first step in trialling such a novel concept is to test the effect of artificial light in a commercial industry in Australian waters. For this, the Moreton Bay Otter Trawl Fishery (MBOTF) was chosen as a representative tropical prawn trawling location where the effect of artificial light on bycatch species can be examined.

The Moreton Bay Otter Trawl Fishery (MBOTF) is a commercial fishery that operates in the inshore waters of the South-Eastern coast of Queensland (DAFF 2013). This fishery allows fishers to retain certain byproduct species including: blue swimmer crabs (*Portunus armatus*), three-spot crabs (*Portunus sanguinolentus*), cuttlefish (*Sepia* spp.) and mantis shrimp (*Oratosquilla* spp.) (Courtney *et al.* 2012). Every prawn trawl vessel operating in Queensland waters must have at least one compliant BRD installed (Roy and Jebreen 2011). This strategy was introduced as part of the Fisheries (East Coast Trawl) Management Plan 1999 since the capture of bycatch in prawn trawl fisheries has become a major concern. This is because they are recognised to be one of the least selective forms of fishing (AFMA 2009). The MBOTF interacts with a range of species including turtles, sea snakes, sharks, rays and saw fish as well as hundreds of species of fish and invertebrates (AFMA 2009).

To start the investigation of the use of artificial light as an effective BRD tool, the change in catch rates of fish species is to be examined in a tropical Australian prawn trawl fishery. The aim of this chapter, therefore, is to test the effectiveness of using artificial light on a commercial prawn trawler in the Moreton Bay Otter Trawl Fishery in Queensland, by measuring the catch rates of species that have been identified as bycatch to the industry.

2.2. Methodology

2.2.1. Sampling area

Sampling took place west of Moreton Island within Moreton Bay, QLD (Figure 1). Fishing depths ranged between 43 and 95 m. The sampling was conducted in March 2014 and during the week of sampling, high tide was 2.18 m and low tide was 0.61 m while the moon phase was in the last quarter. See Appendix 2.6.1 for full cruise details.

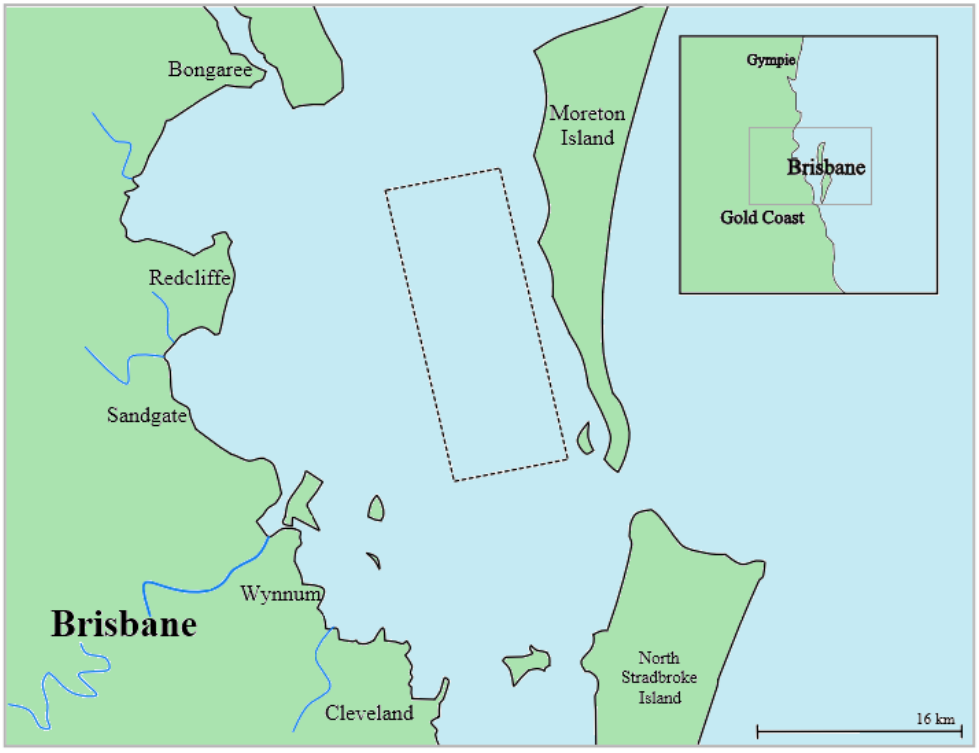

Figure 1: Location of trawling within black box marked with dotted lines, Moreton Bay, Queensland (illustration by Darcie E Hunt 2016).

2.2.2. Sampling gear

Trials were conducted on board a commercial fishing vessel, the *Mark Twain*, during March 2014. A quad rig set up was used with boards spreading two 4 meter nets on both side of the vessel (Figure 2). A total of eight light producing units were used during sampling, 2 on each of the 4 nets.

Each light unit was attached to the headline of each net with shackles and was positioned 0.2 m in from the wing-end of each headline. The cables were cable-tied to the headline to reduce drag and to the skid between the nets. Shackles were sufficient for attachment to the headline and the cables were loosely attached to the net with cable ties.

Each light unit weighed 4 kg and 26 cm in length (Figure 3 and 4). Each light unit had 9 W LEDs operated at 600 lumens light intensity from the forward facing LEDs only and a wireless remote controlled the on/off function. Each LED had a 100 degree beam angle and 5000K colour temperature. Each light unit was powered by one 14.8V internal lithium battery. See Appendix 2.6.1 for full design criteria.

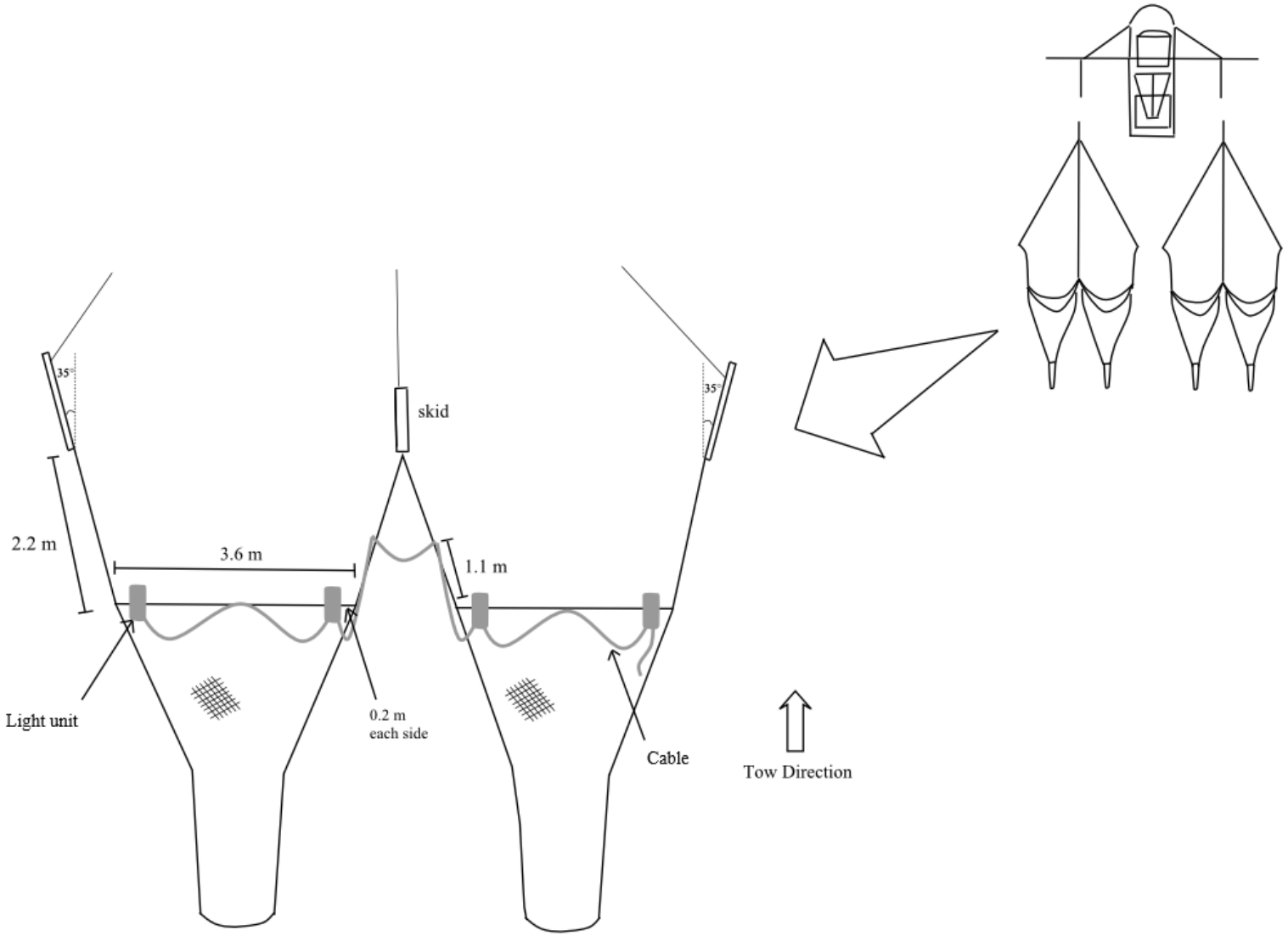

Figure 2: Schematic of light BRD arrangement on headlines (illustration by Darcie E Hunt).

Figure 3: Top view of the light unit with the LED on the right, and end cap on the left; the red subcon connector attaches the set of eight units together; black layer is 1.5 cm thick foam to neutralise buoyancy (photograph: Darcie E Hunt).

Figure 4: A unit attached to a headline with shackle from the front of the light unit; cable connects the units from the red subcon connector at the ear of the unit (photograph: Darcie E Hunt).

2.2.3. Data collection

Four paired tows were conducted each night for 3 consecutive nights. Tow duration varied between 2½ - 3 hours at speeds ranging from 2.5 to 3.2 knots. Due to some difficulties with the operation of the lights, the side with the lights turned on could not be randomly allocated. Full details of each shot are provided in Table 1. Shots 1 and 3 were removed from the dataset for the purpose of analysis as there were no lights on for either net. Shot 8 was removed due to unexpected light malfunction. The catch rates for the port were compared against the starboard for each shot. When the catch reached the deck it was spilled into the sorting tray, with the catch from either side of the vessel kept separate by using a wooden slat. The catch was sorted for crabs first then prawns. Fish bycatch was sorted by species, counted and weighed with on-board motion compensated marine scales (Wedderburn) to the accuracy of 0.05 kg.

Table 1: Individual trawl log data for all shots completed during the cruise in Moreton Bay, QLD.

Date	Shot number	Light status	Start time	End time	Trawl duration (mins)	Start latitude	End latitude	Start longitude	End longitude	Trawl speed (knots)	Depth min (m)	Depth max (m)
23/03/2014	1	Neither	1830	2120	170	27"09'810	27"11'683	153"19'518	153"18'287	3	45	47
23/03/2014	2	Port	2140	0000	140	27"11'827	27"12'242	153"19'288	150"18'806	3.2	43	47
24/03/2014	3	Neither	0016	0300	164	27"12'242	27"11'046	153"18'606	151"18'245	3.2	64	75
24/03/2014	4	Port	0317	0555	158	27"17'289	27"10'799	153"23'224	153"48'897	3	65	90
24/03/2014	5	Starboard	1825	2100	156	27"15'041	27"13'657	153"17'839	153"19'782	2.6	51	67
24/03/2014	6	Port	2115	12am	165	27"15'461	27"15'516	153"20'795	153"20'936	2.9	53	77
25/03/2014	7	Starboard	0015	0300	165	27"17'863	27"14'156	153"21'505	153"23'747	3	64	79
25/03/2014	8	Port	0315	0610	175	27"16'361	27"10'746	153"23'670	153"08'670	3	55	72
25/03/2014	9	Starboard	1808	2056	168	27"16'312	27"14'574	153"17'024	153"19'121	2.9	63.1	73.5
25/03/2014	10	Starboard	2108	0000	172	27"14'574	27"12'579	153"19'121	153"22'712	2.8	76.9	88.7
26/03/2014	11	Starboard	0015	0255	160	27"13'323	27"19'217	153"19'815	153"25'154	2.7	77.9	94.1
26/03/2014	12	Starboard	0322	0553	151	27"19'217	27"15'902	153"25'144	153"24'407	2.5	67	86

2.2.4. Data analysis

Data was standardised as catch per unit area (CPUA) for number (NPUA) and weight (WPUA):

$$CPUA = \frac{C}{a}$$

Where, *C* is catch and *a* is swept area. The swept area (*a*) is found from the following:

$$a = D \times hr \times x^2$$

Where, D is distance travelled, *hr* is the length of the headrope and x^2 is the wing spread (the fraction of the headrope that is equal to the path swept).The head rope length remained a constant of 4 m for all tows and the wing spread was assumed to be 0.5 for all tows. Due to the non-linear path of trawling, distance travelled was calculated using the speed and duration of the tow using the following:

$$D = Speed \times tow\ duration$$

Where, speed was the speed of the boat over ground (converted to km/hr) and tow duration was the bottom time in hours.

Data was analysed in terms of WPUA (kg/km^2) and NPUA (number/km^2). The difference in catch rates between catches with lights on versus lights off (i.e. port and starboard nets, see Table 1) of each tow was analysed using the Wilcoxon signed-rank test ($\alpha = 0.05$). This analysis was used as it is a non-parametric test that looks at the effect on matched pairs. Error bars were presented as standard error of the mean calculated with the following:

$$SEx = \frac{s}{\sqrt{n}}$$

Where, SEx is the standard error of x, *s* is the sample standard deviation and *n* is the number of observations. Total fish bycatch, prawn and crab were analysed as separate groups, then fish species were analysed individually.

A post-hoc power analysis was conducted to observe the statistical power of the tests conducted to compare catch rates. The analysis takes into account the sample size (n), the

effect size (delta), the standard deviation of the pooled data, and the significance level (α=0.05). If the power of the test was less than 0.80, the power analysis was re-run to compute the required sample size to achieve the standard 0.80.

2.3. Results

A total of 10, 106 fish were caught and identified during the fishing operations, with a total weight of 185 kg. Of these fish, 5 174 (51 %) were caught with lights off and 4 932 (49 %) were caught with lights on. For the complete summary of catch data, see Table 2.

Table 2: Mean WPUA (kg/km2) and NPUA (number/km2) of all species caught for all tows with lights on versus lights off. ‘n’ denotes the number of trawls each species was present in.

			Off		On	
Scientific names	**Common names**	**n**	**CPUA (kg/km2)**	**CPUA (number/km2)**	**CPUA (kg/km2)**	**CPUA (number/km2)**
Acanthocepola krusensternii	Red-spotted bandfish	8		135		66
Antennarius sp.	Anglerfish	1		61		
Apistus carinatus	Oscellated waspfish	14	9.37	320	5.44	165
Apogon poecilopterus	Pearly-finned cardinalfish	3	1.61	386		67
Apogon sp.		24	3.10	302	6.50	340
Callionymus moretonensis	Queensland stinkfish	17	251.79	23671	49.93	4329
Carangoides sp.	Trevally	1				79
Caranx sp.	Trevally	12	7.35	107	16.74	253
Chelidonichthys kumu	Bluefin gurnard	4	29.80	208		670
Choerodon sp.	Tuskfish	1	0.00	125		
Cynoglossus sp.	Tongue sole	17	12.90	115	47.81	369
Dentex spariformis	Saffronfin sea bream	3	3.32	66	3.35	67
Dicotylichthys punctulatus	Three-barred porcupinefish	7	10.04	67	17.60	107
Fistularia commersonii	Bluespotted cornetfish	2		64		
Gonorynchus greyi	Beaked salmon	2	35.23	70		
Herklotsichthys sp.	Herring	9	1.21	121	2.37	218
Leignathus moretonensis	Moreton bay ponyfish	11	31.99	5732	134.16	29974
Maxillicosta whitleyi	Whitley's scorpionfish	1		134		
Minous sp.	Stingfish	12	9.22	184	10.29	206
Octopus sp.	octopus	1		74		
Oratosquilla spp.	mantis shrimp	18	166.25	5646	255.49	8670
Paramonacanthus filicauda	Threadfin leatherjacket	19	46.44	3029	24.70	1406
Parapercis sp.	grubfish	1	3.70	74		
Penaeidae spp.	Assorted prawns	6	54.70		34.89	
Penaeus esculentus	Tiger prawn	18	667.12		745.03	
Photololigo sp.	squid	10	30.02		77.98	

Platycephalidae sp.	Flathead	19	31.34	1468	31.19	1010
Platycephalus sp.	Australian threadfin	1			31.35	63
Polydactylus multiradiatus	Bluefish	18	5.31	136	121.99	2915
Portunus spp.	Crab	24	945.82	6982	1120.05	8412
Priacanthus macracanthus	Red bigeye	18	15.29	263	30.44	527
Psettodes sp.	flounder	19	67.69	642	9.03	342
Pterygotrigla andertoni	Painted latchet	4		64		222
Sardinella sp.	Sardinalla	5			7.86	135
Saurida micropectoralis	Shortfin lizardfish	2	30.79	185	75.76	303
Saurida undosquamis	Brushtooth lizardfish	19	180.91	2595	164.41	2654
Scomber australasicus	Blue mackerel	2				66
Sepia sp.	cuttlefish	16	75.74	1443	103.83	1888
Sillago sp.	whiting	14	38.99	560	59.15	1060
Sphyraena sp.	pike	1			3.35	67
Terapon sp.	Terapon	4	18.58	867	9.21	307
Tetractenos sp.	toadfish	5	3.26	65	3.52	70
Tetrasoma sp.	boxfish	1	0.00	61		
Thenus orientalis	Moreton bay bug	2	0.00	61	27.27	
Trachurus declivis	jack mackerel	4	3.13	125	3.39	203
Trygonoptera sp.	stingarees	3	10.46	167		
Unidentified		24	25.68	50	34.01	191
Upeneus tragula	bartail goatfish	12	23.90	1097	17.00	813

2.3.1. Catch comparisons

There were no statistical differences in WPUA (kg/km^2) for fish (V= 29, p = 0.496), prawn (V= 15, p = 0.426) or crab (V= 14, p = 0.359) caught in prawn trawl tows with lights on versus lights off (Figure 5). The NPUA (number/km^2) of individuals caught with lights on versus lights off was also not statistically significant for fish (V= 36, p = 0.129) and crab (V = 16, p = 0.496) (Figure 6). The numbers of prawns were unable to be quantified and so are not included in the analysis. Post-hoc power analysis revealed that the statistical power for total fish WPUA (power = 0.08), fish NPUA (power = 0.04), prawn WPUA (power = 0.08), crab WPUA (power = 0.15), crab NPUA (power = 0.11) were all less than the required level of 0.80.

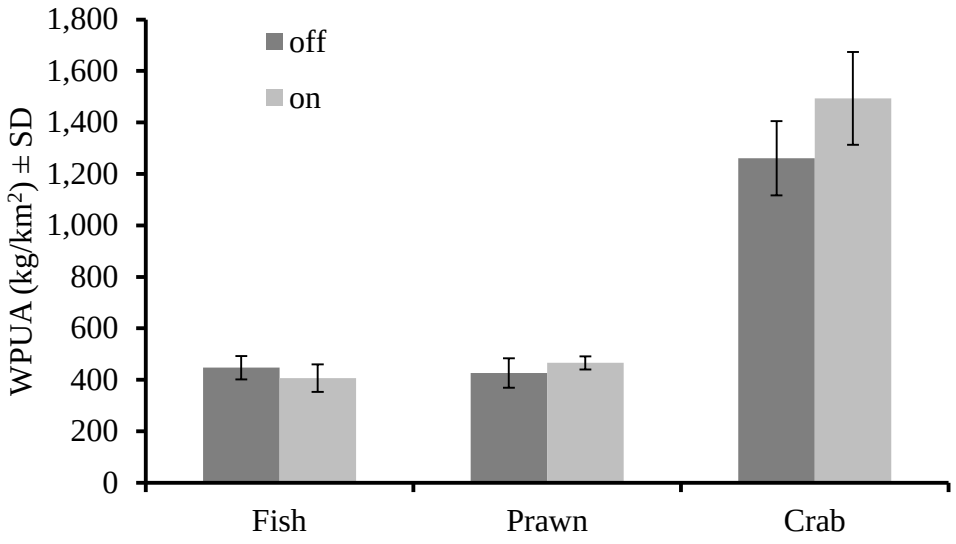

Figure 5: Mean WPUA (kg/km^2) ± SE of total fish catch, prawns and crabs with lights on versus lights off.

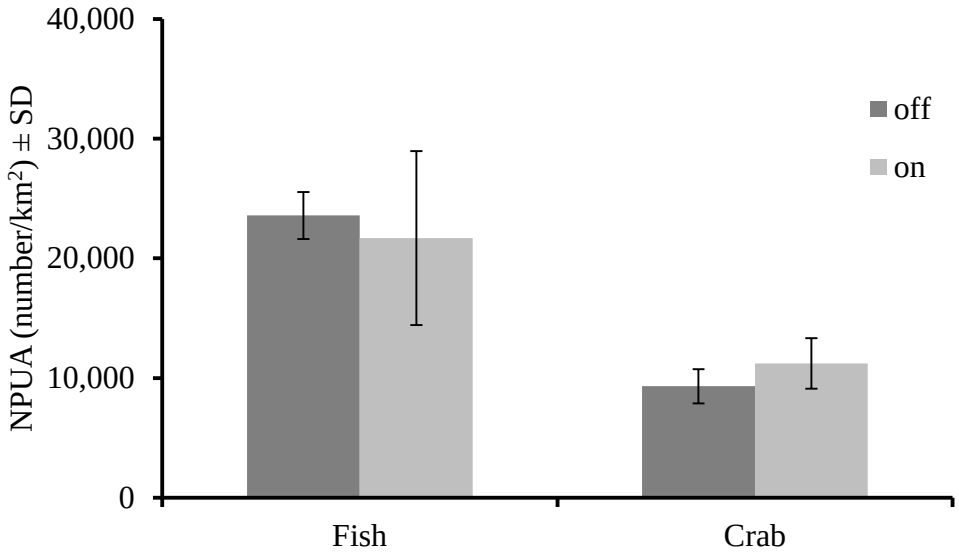

Figure 6: Mean NPUA (number/km^2) ± SE of total fish catch and crabs with lights on versus lights off.

2.3.2. Species comparisons

There were 58 species of fish identified and of these fish, when comparing lights on versus off, 5 species were found to have significantly different WPUA (kg/km^2) and 6 had significantly different NPUA (number/km^2) (Table 3).

Table 3: Wilcoxon signed-rank test statistics for both weight and numbers. Only species found to differ significantly between lights on and lights off are shown.

		WPUA (kg/km^2)		NPUA (no./km^2)	
Species	n	V-value	*p-value*	V-value	*p-value*
Paramonacanthus filicauda	9	43	0.00781	44	0.00781
Callionymus moretonensis	8	35	0.01563	36	0.00781
Flounder spp.*	8	27	0.03906	-	-
Cynoglossus sp.	8	0	0.00781	0	0.02249
Polydactylus multiradiatus	8	0	0.00781	1	0.01563
Priacanthus macracanthus	9	-	-	3	0.01563
Apistus carinatus	7	-	-	21	0.03603

*Consisting mainly of *Arnoglossus waitei* & *Pseudorhombus argus*.

The mean weight of *P. filicauda*, *C. moretonensis* and the flounder species (*A. waitei & P. argus*) had decreased by 47 %, 82 % and 87 %, respectively. However, the mean weight of *Cynoglossus sp.* and *P.multiradiatus* increased by 75 % and 96 % respectively (Figure 7).

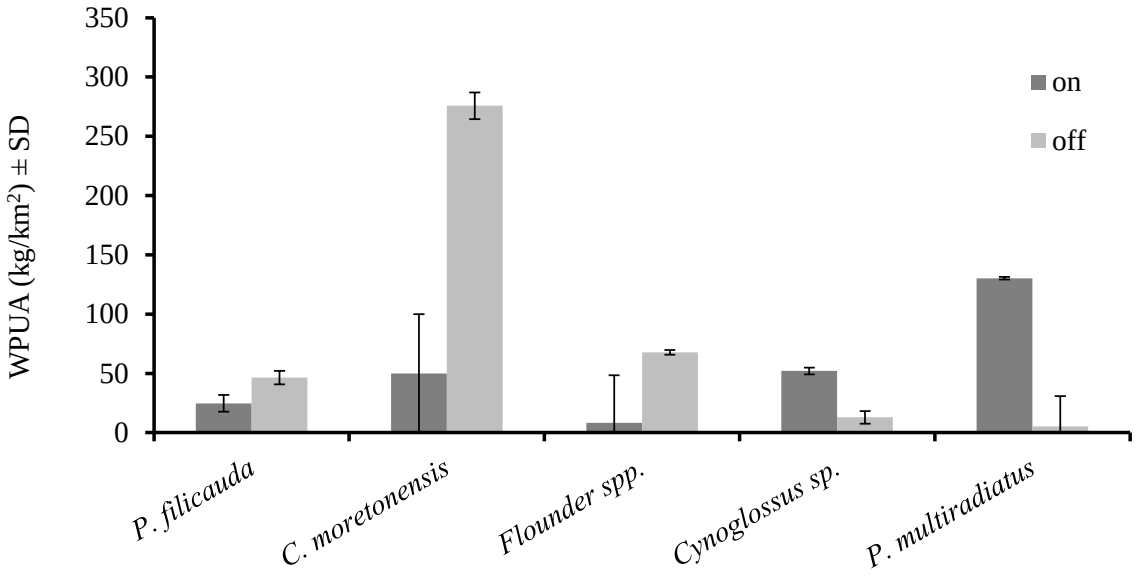

Figure 7: Mean WPUA (kg/km^2) ± SE of teleost species with lights on versus lights off.

In terms of numbers, *P. filicauda*, *A. carinatus* and *C. moretonensis* decreased by 54 %, 48 % and 83 %, respectively. However, the mean number of *Cynoglossus sp.*, *P.multiradiatus* and *P. macracanthus* increased by 72 %, 96 % and 50 %, respectively (Figure 8 and Figure 9).

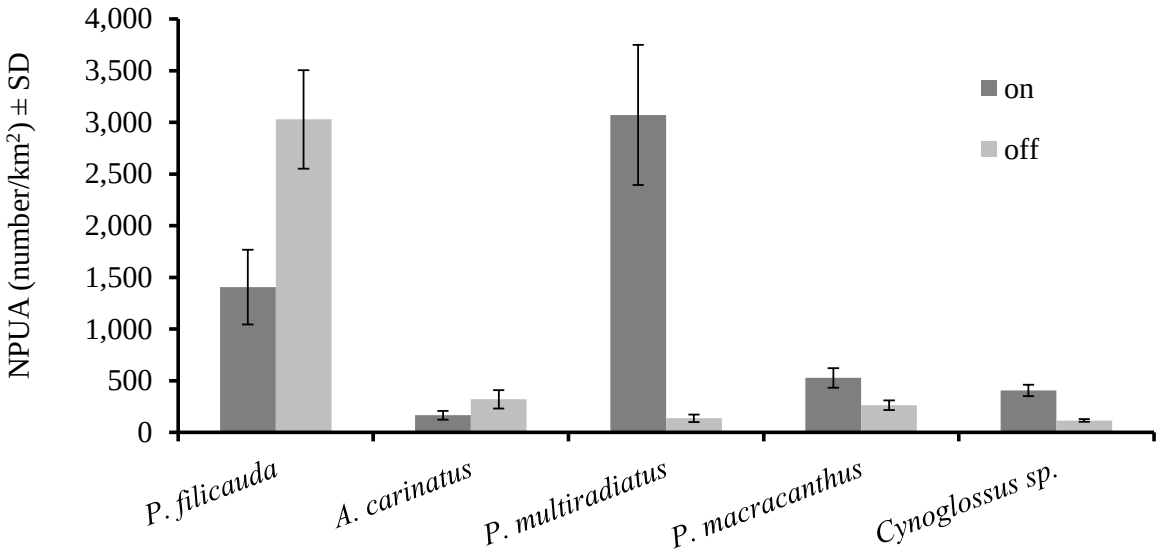

Figure 8: Mean NPUA (number/km^2) ± SE of teleost species with lights on versus lights off.

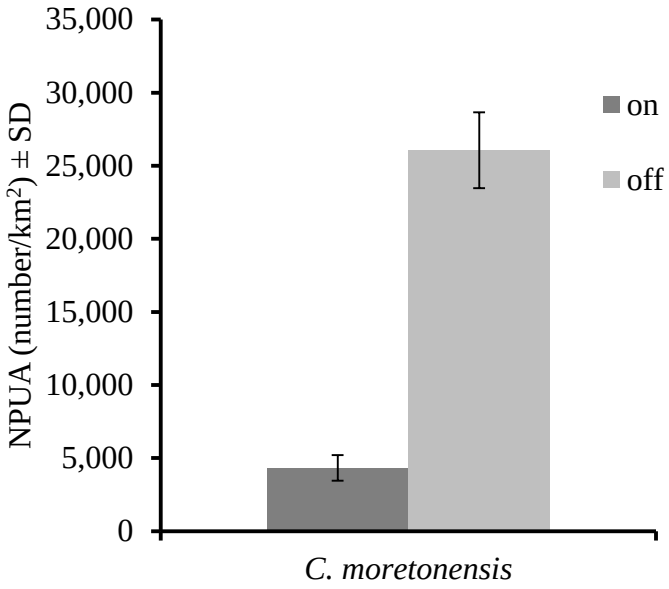

Figure 9: Mean NPUA (number/km^2) ± SE of *C. moretonensis* with lights on versus lights off. This species was plotted separately due to the much higher range of NPUA (number/km^2).

2.4. Discussion

Trials of the light BRD in the Moreton Bay commercial prawn trawl fishery have shown preliminary results for the effect of light on tropical fish species. Results from these trials support the concept of using light as a BRD, however the operational issues of the light units used in this chapter need to be addressed.

Total bycatch, in terms of both WPUA and NPUA, did not change significantly. As expected, however, the difference in catch varied by species. This was also found to be the case in a study on artificial lights (Clarke *et al.* 1986), which found that although total catch was not found to be significantly different, species caught in sufficient sample sizes were. Limited statistical power due to the modest sample size in the present study (n = 9) may have limited the ability to detect the significant difference of the statistical comparisons conducted. A post-hoc power analysis revealed that, to obtain statistical power at the recommended 0.80 level, a sample size of approximately 201 and 1063 replicate tows would be needed for total fish catch in terms of WPUA and NPUA, respectively.

2.4.1. Individual species

There were seven species that were significantly different in terms of weight or numbers or both. At first glance these fish are a mix of demersal and benthic species. None of these species are schooling species. The differences between the flounder species (*A. waitei & P. argus*) and *Cynoglossus sp.* (the former increasing and the latter decreasing) suggests that it is not related to morphology.

As *Cynoglossus sp.* and the flounder species (A. *waitei & P. argus*) are both flatfish, their reaction to fishing gears would have been expected to be similar. However this was not the case here because the difference between species is due to their ability to detect the trawl as well as to avoid it.

Three of the seven species significantly increased with the use of artificial light on the prawn trawl net. The catch rates of *Cynoglossus sp.*, *P.multiradiatus* and *P. macracanthus* all increased with the use of light. Although the overall catch of fish decreased, it is still preferable to decrease each fish species individually. This may be the result of the vision of the fish being negatively affected by the artificial light and is unable to actively swim away from the oncoming trawl gear. They may be disorientated by the intensity of light at the

mouth of the net and therefore capture is more likely (Clarke and Pascoe 1985; Swinney *et al.* 1986). Since most fish have certain levels of light that they are adapted to (as can be seen by habitat depth preferences) the photoreceptor cells responsible for detection of light and colour can be damaged by high intensity light (Clarke *et al.* 1986; Gordon *et al.* 2002).

It must also be considered that individual fish need to not only detect the oncoming trawl but have the necessary means to avoid it. The maximum speed of the fish is the main factor influencing it ability to avoid an oncoming trawl net. There have been no studies done on the swimming speeds of *P. filicauda*, *C. moretonensis*, the flounder species (A. *waitei & P. argus*) and *A. carinatus*, but with an 82 % decrease in WPUA (kg/km^2) it could be said that *C. moretonensis* may have the greatest chance of avoiding the trawl.

2.4.2. Prawns

From the two previous studies conducted on the effect of artificial light on prawn catches in trawl nets there appears to be no significant change in catch rates (Hannah *et al.* 2015; Hargreaves and Herring 1992). This was also the case in this study, as it appeared that the statistical analysis could not detect a significant difference in the catch of prawns with lights on versus lights off. This is likely to be due to the lack of sustained directional swimming in prawns that is seen in most fish species (Hannah *et al.* 2003).

2.4.3. Byproduct

Permitted byproduct species in the Queensland trawl fishery include blue swimmer crabs, cuttlefish, mantis shrimp and Balmain bugs (DAFF 2013). In this particular cruise, the only byproduct species viable for retention were the blue swimmer crabs. In this fishery, 100 kg is permitted to be kept and they are worth approximately $7/kg (Fargher 2008).

The increase in crabs seen in this study can be interpreted in two ways. Firstly as a valuable increase since this species can be sold. However, it could be a negative since the capture of crabs could decrease the amount of usable individuals of the target species. The author observed that as crabs continuously open and shut their claws on the prawns, there is a chance of cutting them in half and rendering them worthless.

2.4.4. Evaluation of BRD Performance

The light BRD as a product did not perform consistently in these trials. Across the three nights of trawling various lights on both sets of nets malfunctioned. As a result, there were

issues with experimental design. Also, the wireless capability may not be ideal in the final design because turning the lights on and off only worked when the wireless dongle on the cable was out of the water. The cable connecting the lights together caused issues in terms of getting caught and ripping holes in the nets. In general the overall design was too large and complex.

Although there was no demonstrable bycatch reduction during these trials, the results show potential for this technology to be developed. It is acknowledged that the future tests should be done with additional rigour and it is suggested that trial tows should be done with lights turned off for both sides of the vessel. This will allow for testing of the assumption that catches are the same on both sides of the vessel. There should also be some examination to check whether the light on one side of the vessel is affecting the capture rates on the other side. The results reported here only reflect the capture of species with one particular light unit and it is anticipated that results may vary if the light used had differing intensity and wavelengths. As such, there is futher research yet to be done to fully understand the possibilities of using light on trawls.

2.4.5. Conclusions

This chapter reports on the use of light as a method for reducing the capture of fish bycatch in the Moreton Bay Otter Trawl Fishery. Although a significant difference was unable to be detected with this experimental design, it was found that there are large changes in catch rates for certain species. Since an overall change in catch was not found, testing in this fishery was discontinued as so not to impact on commercial fishing operations. There was a need to refine the technology of the lights and test them again on more accessable vessels. This was to minimise interruption to commercial fishing practices and also to allow experiments to be conducted closer to the institute the research was based at. Therefore, in the following chapters the effect of the lights will be tested on a research vessel in the temperate waters on North-eastern Tasmania. This will then allow for the investigation into the differences observed between species, for example differences in terms of physiology or morphology.

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2.6. Appendix

Appendix 2.6.1- Design of lights

The light system was designed by the National Centre for Marine Conservation and Resource Sustainability (NCMCRS) and the National Centre for Maritime Engineering & Hydrodynamics (NCMEH) of the Australian Maritime College (AMC) in partnership with Energy Options International (EOI). Its development was funded through an AusIndustry Innovations Grant awarded to UTAS and Energy Options International. The following requirements were developed to guide the design process of the light BRD:

1. Rugged to withstand operating on a commercial vessel, salt water conditions, weather and the trawling process.
2. Easy access to the internal components while at sea.
3. Easily chargeable- with batteries located within each unit.
4. Wireless capable for programming
5. Operates at depths to 500 m
6. LEDs facing three different directions to examine difference in orientation (up forwards and down)
7. LEDs programmable for different light intensities.
8. Easy attachment to the headline.
9. Lights remain on for 12 continuous hours of trawling.
10. The size of each unit needs to be small enough as so to not impact on regular trawling operations.
11. The weight of the device must neutral or positively buoyant as so to minimise the chance of dragging on the headline.
12. The price of each unit must be reasonable in the context of commercial aspirations.

A total of eight units were designed and built using the above criteria. Each unit weighed 4 kg and were 26 cm in length (Figure 1). The unit housing was made from solid aluminium. The batteries used were 14.8V 10Ah LiPO4 battery packs with 1 battery pack per light. The loop at the front of the housing allowed for attachment with a shackle to the headline. The LED housings were placed on top, at the front and underneath the unit to allow for the various orientations. The light intensity of each LED was 600 lumens. Both of these functions,

direction and intensity, were changeable using a remote that controlled the lights with a wireless dongle. Each set of four lights was connected using a cable.

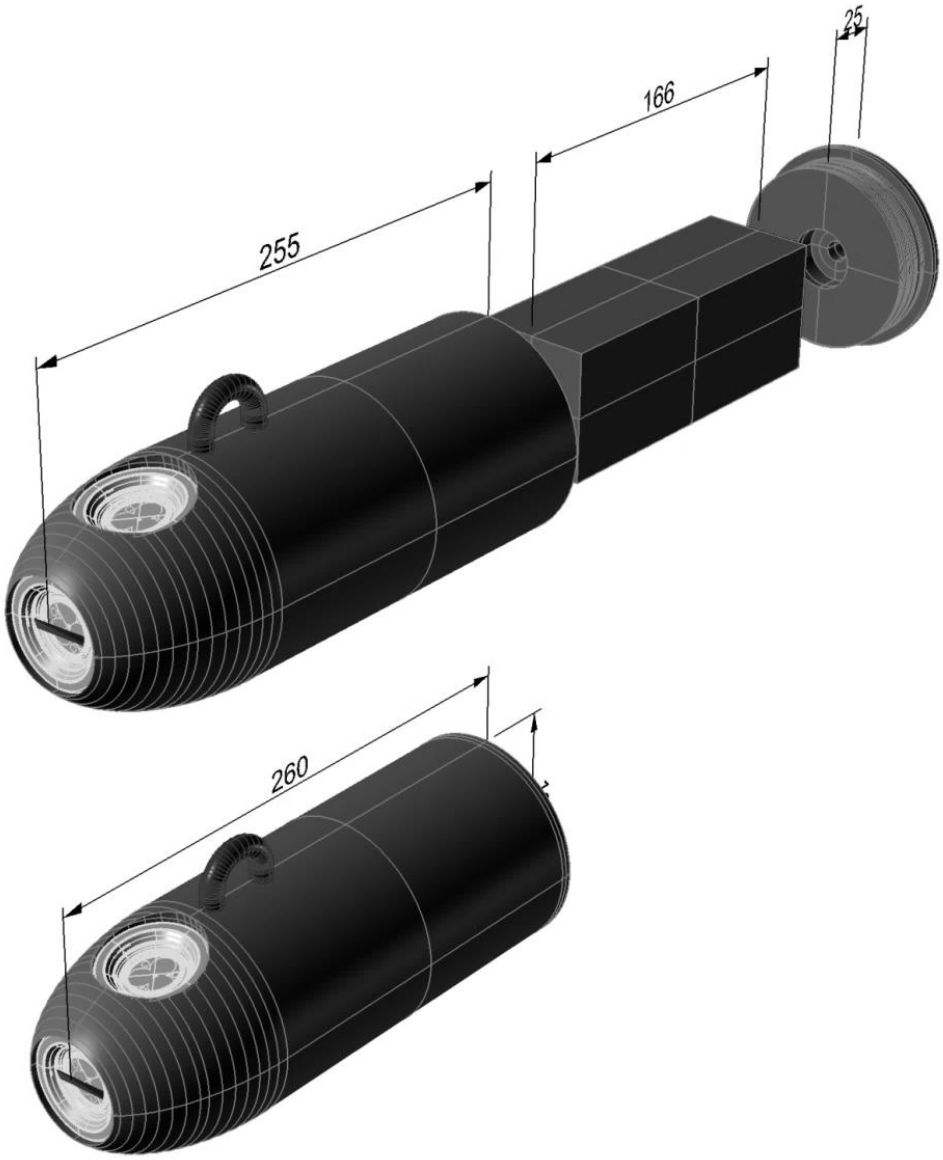

Figure 1: Capsule profile. Housing is one piece moulded aluminium, with nose cone filled with resign to seal LED's in place. Inside is the battery pack and the unit is sealed with the end cap. Battery pack will be mounted in foam block to suit internal shape of capsule (diagrams provided by Energy Options International).

CHAPTER 3: The effect of LED light on shallow water teleost species in North-Eastern Tasmanian waters

3.1. Introduction

Bycatch and discarding are major threats to the sustainability of commercial fisheries around the world. Bycatch is defined as the non-target and illegal fish that may be caught and discarding is the returning of such waste to the sea (DAFF 2000). Over the last couple of decades, many ideas for the reduction of bycatch have been tried, tested and, in many cases, adopted into industry (Eayrs *et al.* 1997). The prawn trawl industry has been at the forefront of the development of bycatch reduction designs. In Australia, the bycatch to prawn ratio can be between 5:1 and 10:1 even with the use of mandatory bycatch reduction devices (BRDs) (Courtney *et al.* 2006; Woodhams *et al.* 2011). Such designs include the Turtle Excluder Device (TED) that is used to reduce the capture of mammals, turtles, sharks and rays (Eayrs *et al.* 1997).

A new concept is now being investigated that uses light to reduce the capture of bycatch species. The theory for using lights is to illuminate the area in front of the trawl, increasing the visual warning of the towed gear and therefore increasing the likelihood of an escape response for various teleost species. Benefits of reducing bycatch include reduced fishing pressure on the bycatch species populations, as well as reduced sorting time and higher quality of the catch of target species (DAFF 2000). Under the water it is also beneficial to have a reduced number of fish passing through the netting in the trawl as there is still some chance of mortality associated with interacting with the gear.

Very few have attempted to test the effect of artificial light on the catch composition of a trawl net (Clarke *et al.* 1986; Gordon *et al.* 2002; Hannah *et al.* 2015). For those that have, there have been varied results. Clarke *et al.* (1986) for example, found no difference on overall catches while Hannah *et al.* (2015) saw a large decrease in catch for some of the species that were examined. There was, however, a common conclusion amongst these studies, that the the differences in fishes (in terms of morphological, physiological and behavioural) should be further studied to explain variation in catch rates (Clarke *et al.* 1986; Gordon *et al.* 2002; Hannah *et al.* 2015).

The use of artificial light as a BRD was introduced in the previous chapter as a way of potentially reducing the capture of teleost species in a prawn trawl net. This chapter extends on that study by providing the details on fish that will be used in the next chapters. Although there are no prawn trawl fisheries in the temperate waters of North-Eastern Tasmania, by

studying the same fish species across the experiments outlined in the next four chapters comparisons can be made between the physiology of the fish and catch rates with the use of artificial light.

The aim of this chapter, therefore, is to describe the effect of artificial light on overall catch of eight species of interest in a trawl in the temperate waters of North-Eastern Tasmania. The effect on the catch rates of individual teleost species as well as total overall catch will be examined.

3.2. Methodology

3.2.2. Samplng area

Sampling was conducted on three separate cruises. During June 2013 and May 2014, the data was collected off the east coast of Flinders Island, Tasmania while the cruise in November 2014 was conducted on the east coast (Figure 1). Trawling was conducted over two nights for the cruises in June 2013 and May 2014, and across three nights for the cruise in November 2014 (see Appendix 3.6.1 for full details). The average water depth was 34 m and the average speed of all tows was 3.3 knots (speed over the ground). For all cruises there was <1 m swell and gentle to moderate breeze according to the Beaufort scale (Oliver 2005) and cloud cover varied from night to night (between 1- 8 octares). The moon phase in June 2013, May 2014 and November 2014 were last quarter, full moon and first quarter, respectively.

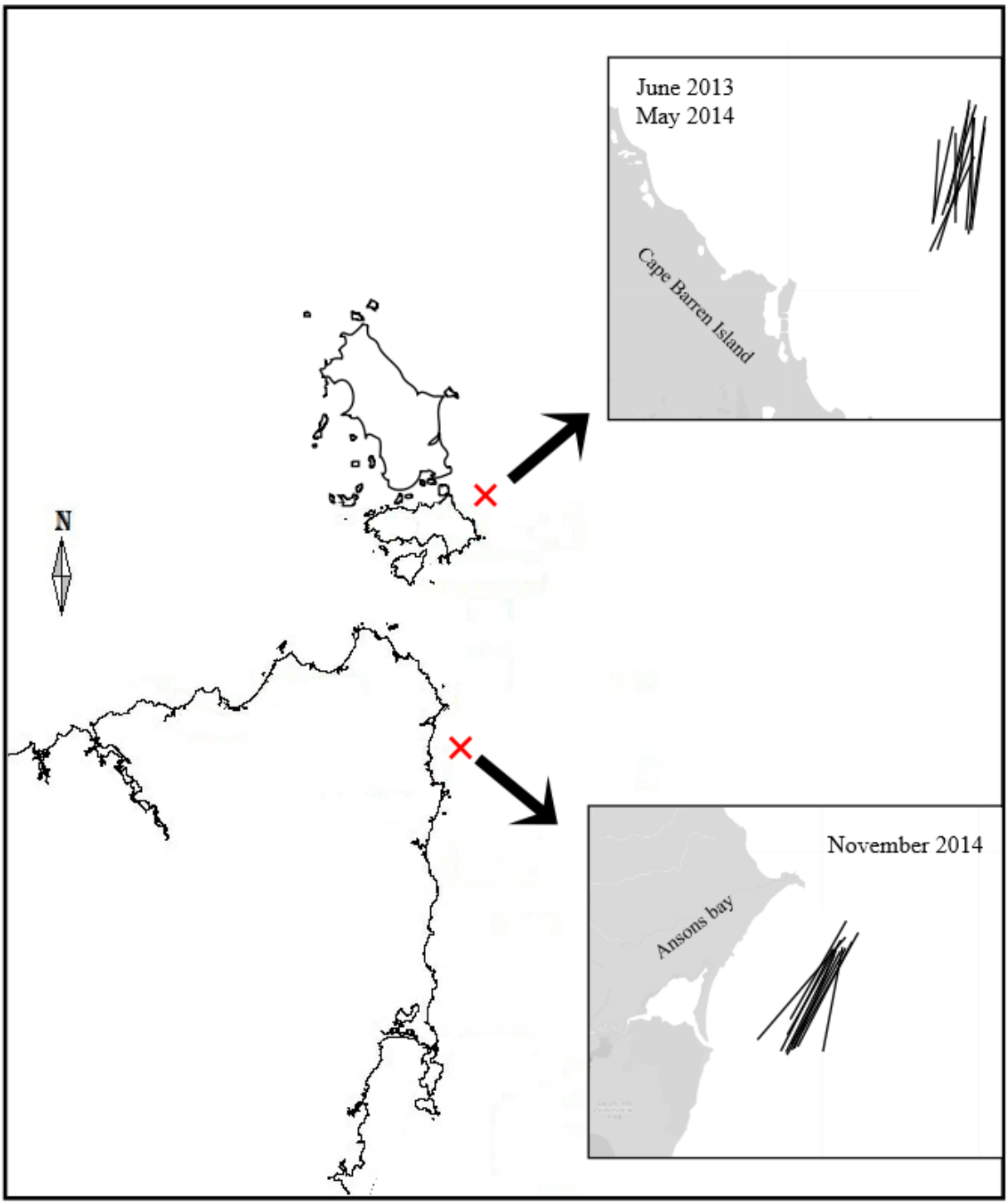

Figure 1: A map showing the location of the trawls conducted in North-Eastern Tasmania. The three different cruises are displayed with the arrows (illustration by Darcie E Hunt).

3.2.2. Sampling gear

Sampling was conducted on board the 34 m fisheries training vessel, *FTV Bluefin*. The vessel was equipped with one 14 meter Florida flyer demersal prawn trawl net. The body of the tapered trawl net was made of 50 mm stretched mesh with a 100 by 45 mesh codend of 40 mm stretched mesh (Figure 2). The net was rigged with 1.2 m bridles and Bison otter boards. A new and improved design of light BRD was used for this experiment (Figures 3 and 4). For design criteria, see Appendix 3.6.2. Lights that were turned off were left attached to the net. The total number of tows was 24 (12 with lights on and 12 with lights off).

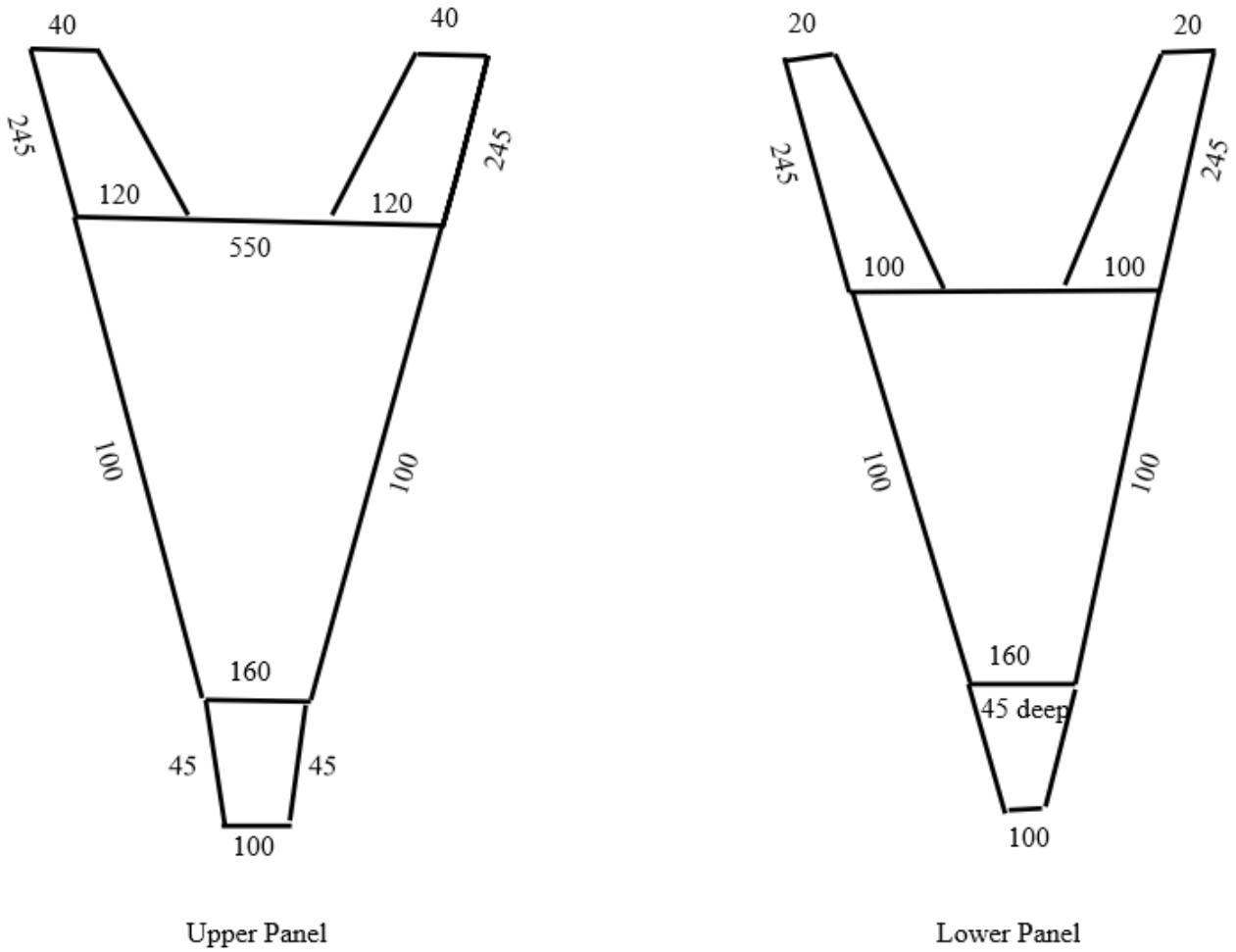

Figure 2: Schematic of the tapered prawn trawl net used during sampling trips. Values represent the number of meshes for each dimension (illustration by Darcie E Hunt).

Figure 3: Photograph of the final design. Forward facing LED with loop for shackling to the net on the right. Connectors at the rear end of the unit are protected with a flexible plastic mesh and hose clamp (photograph: Darcie Hunt).

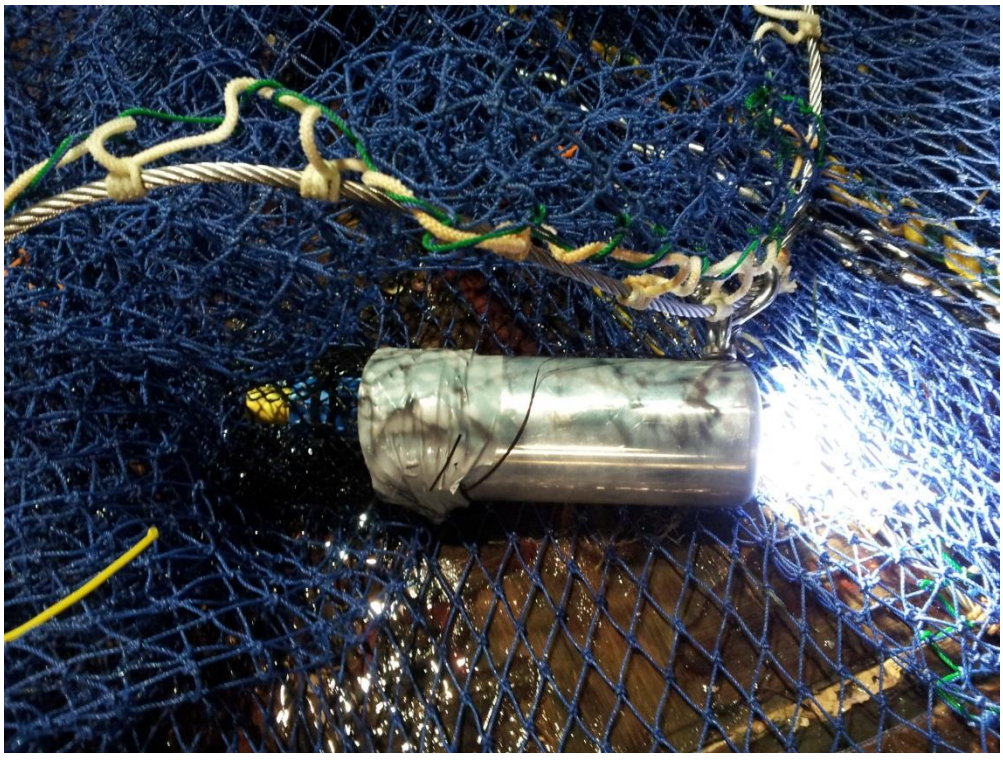

Figure 4: Unit attached to net with shackle. ‘Active’ dongle is plugged in and activates the light (photograph: Darcie Hunt).

3.2.3. Data collection

From sunset until sunrise, 45 minute alternating trawls were conducted with the use of lights on versus lights off being randomly allocated for each tow. For each tow, every individual catch item was sorted by species and counted. Total weights were then measured with on-board motion compensated marine scales (Wedderburn) to the accuracy of 0.05 kg. Length measurements were made of the eight species of interest (every individual) to the nearest centimetre using measuring boards. The species of interest were chosen to represent a variety of different species (in terms of morphology and taxonomy) that were present in sufficient number in each tow. These species were: roundsnout gurnard *Lepidotrigla mulhulli*; crested flounder *Lophonectes gallus*; sand flathead *Platycephalus bassensis*; eastern school whiting *Sillago flindersi*; tiger flathead *Neoplatycephalus richardsoni*; Degen's leatherjacket *Thamnaconus degeni*; silver biddy *Parequula melbournensis*; and jack mackerel *Trachurus declivis*, Figure 5.

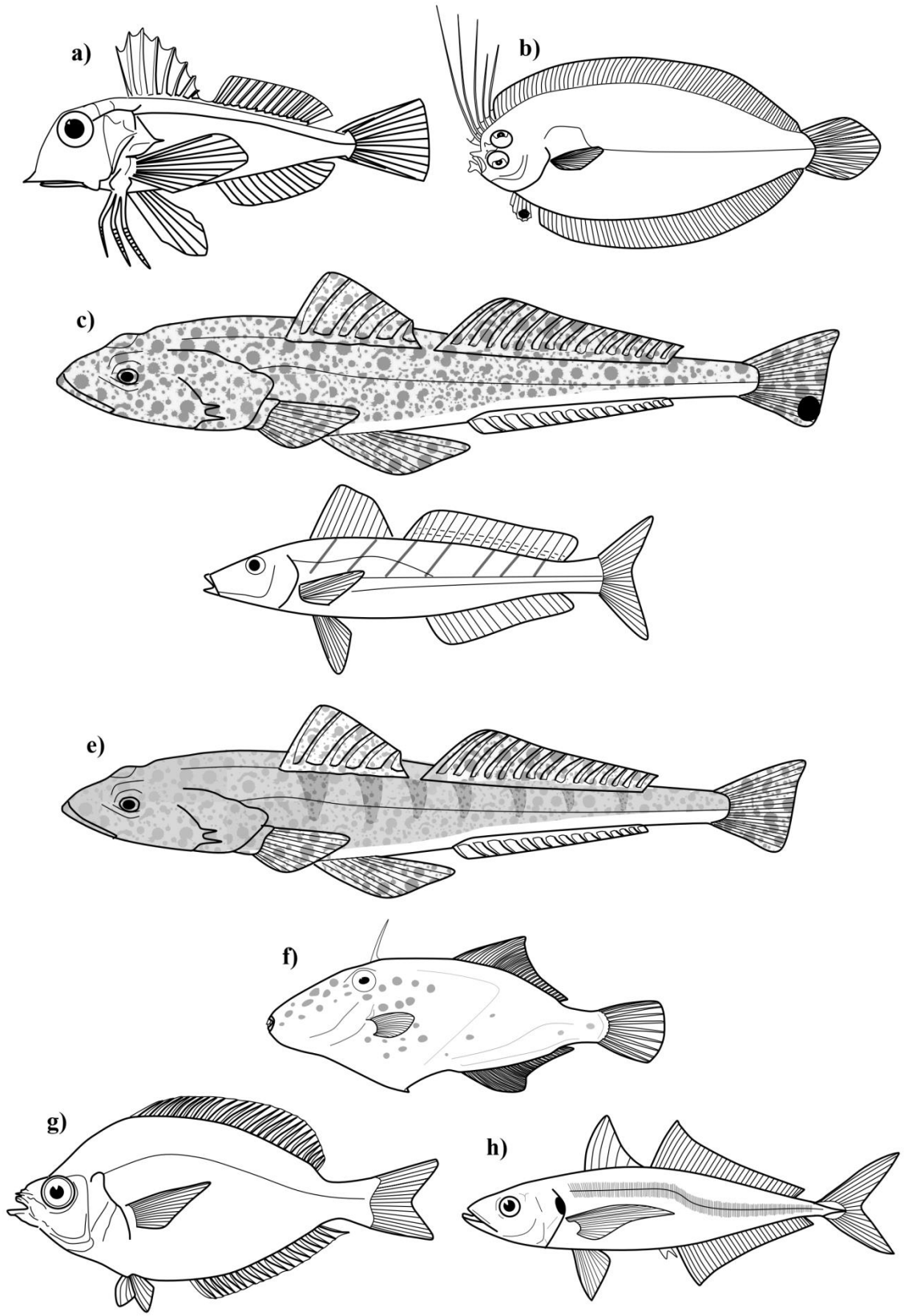

Figure 5: Pictures of species studied in this chapter; a) *L. mulhulli*; b) *L. gallus*; c) *P. bassensis;* d) *S. flindersi*; e) *N. richardsoni*; f) *T. degeni*; g) *P. melbournensis*; and h) *T. declivis* (illustrations by Darcie E Hunt).

3.3.4. Data Analysis

The catch data for each tow was standardised by calculating the catch per unit area (CPUA) for both weights (WPUA) and numbers (NPUA) by using the formula of Sparre and Venema (1998):

$$CPUA = \frac{C}{a}$$

Where, *C* is catch (in either kg or number) and *a* is swept area (km^2). The swept area (*a*) is found from the following:

$$a = D \times hr \times x^2$$

Where, D is distance travelled, hr is the length of the headrope (km) and x^2 is the wing spread (the fraction of the headrope that is equal to the path swept). As per Pauly (1980), a wing spread (x^2) of 0.5 was used. It was assumed that wing spread remained constant during each of the tows. The exact distance (D) of each tow can be calculated the formula of Sparre and Venema (1998):

$$D = 60 \times \sqrt{(Lat1 - Lat2)^2 + (Long1 - Long2)^2 \times cos^2(0.5 \times (Lat1 + Lat2))}$$

Where, *Lat1* is the start latitude, *Lat2* is the end latitude, *Long1* is the start longitude and *Long2* is the end longitude coordinates (all in degrees).

A nested ANOVA was used to test the effect of tow direction and cruise on catch rates. No significant difference was found which allowed for catches to be combined and analysed together.

The CPUA was calculated for both weight (kg) and number of fish for the catch for each of the eight species of interest in each tow, and used for statistical analysis. Normality of variances was tested with the Shapiro-Wilk's test of normality and equality of variances was tested with the Levene's Test for Equal Variances. For those species that were found to be not normally distributed or had unequal variances, the data was transformed with either square-root or natural-log transformation.

An independent t-test was then used to detect significant differences between CPUA with lights on versus lights off for each of these factors (weights and numbers) ($\alpha = 0.05$). For the species that could not be transformed successfully (i.e. still did not have equal and normal

variances), Welch's t-test was used instead. A Kolmogorov-Smirnov test (K-S test) was used to compare the length frequency distributions for catch of each of the species of interest with lights on versus lights off. Also, an independent t-test was used to compare the mean lengths of fish caught with lights on versus off. All statistical analysis was completed using the statistical program R (version 2.15.3). Error bars were presented as standard error of the mean calculated.

A post-hoc power analysis was conducted to observe the statistical power of the tests conducted to compare catch rates. The analysis included the sample size (n), the effect size (delta), the standard deviation of the pooled data, and the significance level (α=0.05). If the power of the test was less that 0.80, the power analysis was re-run to compute the required sample size to achieve the standard 0.80.

3.3. Results

3.3.1. Catch composition

A total of 53 species of teleosts, elasmobranchs and crustaceans that had a combined catch of 1361.4 kg were caught during the 24 tows. The total area trawled was 0.7577 km^2. For the full list of species caught during sampling, see Appendix 3.6.3.

A priori tests demonstrated that the variances of CPUA's for all the species, except *S. flindersi,* were not normally distributed and not equal. The weights and numbers were therefore transformed (Table 2). There was a significant difference between total catch with lights on versus lights off for both WPUA (kg/km^2) ($df=22$, $t=5.568$, $p<0.01$) and NPUA ($numbers/km^2$) ($df=22$, $t=6.378$, $p<0.01$). Using the light BRD, the weight of total fish was halved from 85 to 44 kg/km^2 (Figure 6) and the number of fish was reduced by 40%, from 597 to 346 $fish/km^2$ (Figure 7). Post-hoc power analysis revealed that the statistical power for total fish WPUA (power = 0.94), and fish NPUA (power = 0.96) were all greater than the required level of 0.80.

Differences for individual species vary for both weight and numbers (Table 3 and Table 4). The weights of *N. richardsoni*, *P. bassensis* and *P. melbournensis* were reduced by 70%, 66% and 62% respectively (Figure 8). The numbers of *N. richardsoni*, *P. bassensis*, *P. melbournensis* and *S. flindersi* were reduced by 68%, 75%, 62% and 57% (Figure 9 and Figure 10).

Table 2: Transformations used for each species based on *a priori* tests.

Summary	Weight	Number
N. richardsoni	Square-root	Square-root
P. bassensis	Square-root	Square-root
L. gallus	Welch's t-test	Natural-log
P. melbournensis	Square-root	Natural-log
S. flindersi	Original	Original
T. declivis	Natural-log	Welch's t-test
T. degeni	Welch's t-test	Welch's t-test
L. mulhulli	Welch's t-test	Welch's t-test

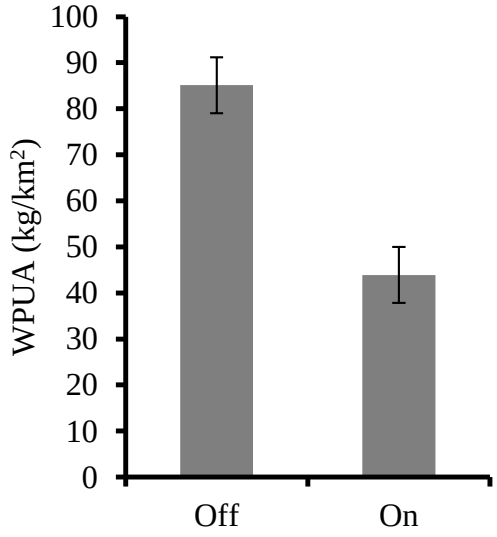

Figure 6: Mean shot weight ±SE (kg/km^2) for total fish bycatch caught with lights on versus lights off.

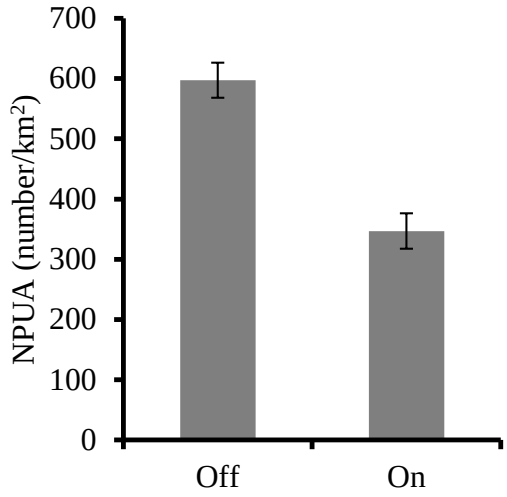

Figure 7: Mean shot abundance ±SE (number/km^2) for total fish bycatch caught with lights on versus lights off.

Table 3: Total WPUA (kg/km^2) and NPUA (numbers/ km^2) for the eight species of interest caught with lights on versus lights off, across all 24 tows.

		Total WPUA (kg/km^2)		Total NPUA (No./km^2)	
Species	No. Tows	Lights Off	Lights On	Lights Off	Lights On
P. richardsoni	24	72.3	19.6	259.7	80.7
P. bassensis	24	79.1	23.3	297.2	65.1
L. gallus	24	2.7	3.0	203.5	80.7
P. melbournensis	24	104.0	38.5	2109.8	773.0
S. flindersi	12	112.9	48.8	924.5	378.3
T. declivis	24	509.4	35.2	2825.8	320.1
T. degeni	24	114.1	134.2	2040.1	2246.1
L. mulhulli	24	116.9	132.6	1801.9	2009.2

Table 4: Parameters for the independent t-test analysis of eight bycatch species caught with lights off and on, for both WPUA (weight/ km^2) and NPUA (numbers/ km^2). Asterisk indicates significantly different result (based on transformed data).

	WPUA (kg/km^2)			NPUA (Numbers/km^2)		
Species	*df*	*t-value*	*p-value*	*df*	*t-value*	*p-value*
L. gallus	22	0.32	0.749	22	1.32	0.199
L. mulhulli	21	0.63	0.534	22	0.89	0.384
P. bassensis	22	2.08	0.049*	22	3.20	0.004*
P. melbournensis	22	2.67	0.014*	22	2.80	0.011*
P. richardsoni	22	2.55	0.018*	22	2.94	0.008*
S. flindersi	10	2.10	0.062	10	2.30	0.044*
T. declivis	22	1.80	0.085	22	1.84	0.079
T. degeni	22	0.44	0.668	22	0.28	0.783

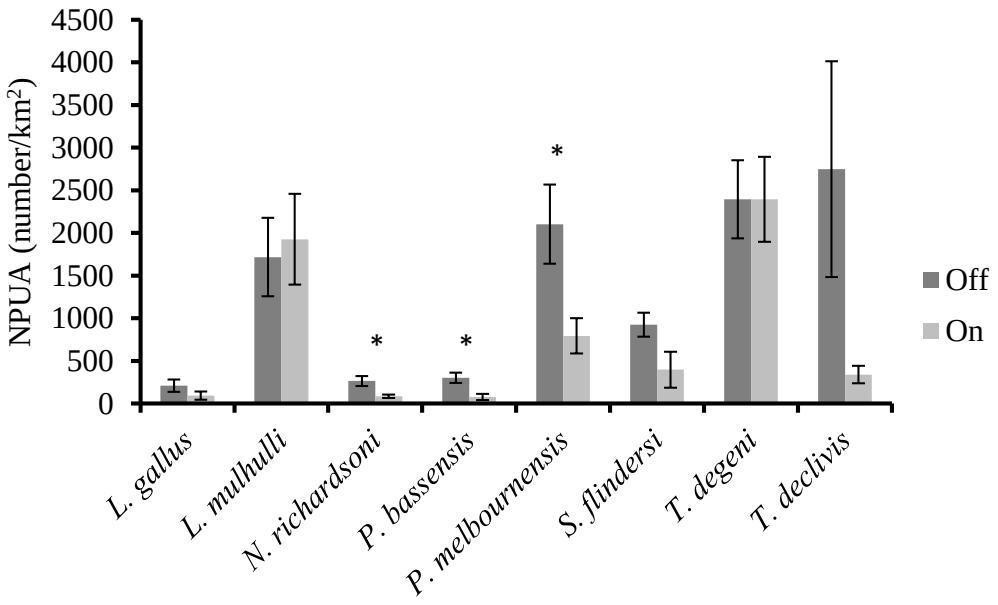

Figure 8: Mean shot NPUA ±SE (number/ km^2) for eight bycatch species caught with lights on versus lights off. Asterisks indicate species that are significantly different with lights on versus off.

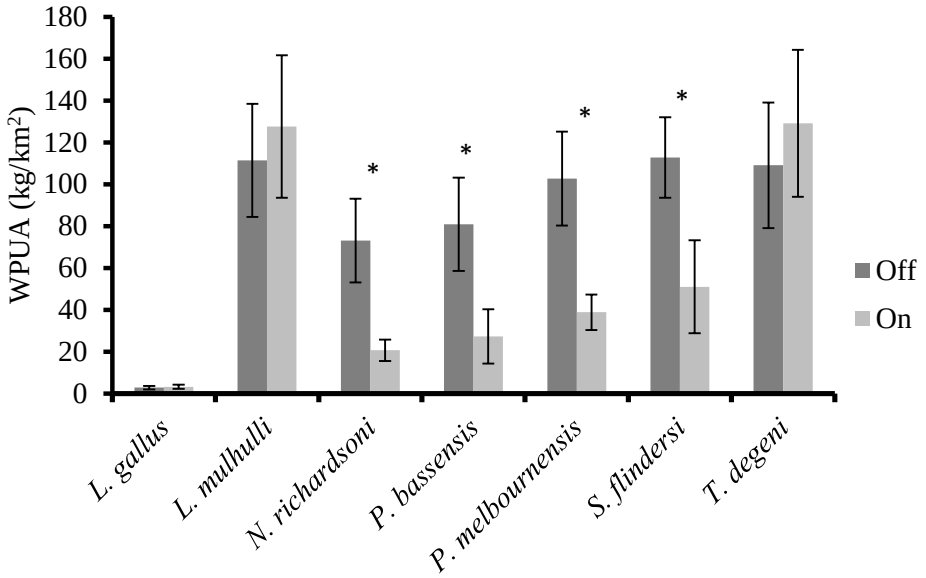

Figure 9: Mean shot WPUA ±SE (kg/km^2) for seven of the eight bycatch species caught with lights on versus lights off. Asterisks indicate species that are significantly different with lights on versus off (based on transformed data).

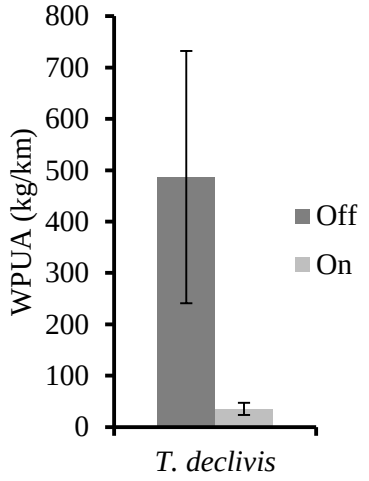

Figure 10: Mean shot WPUA±SE (kg/km^2) for *T. declivis* caught with lights on versus lights off. This species was plotted separately due to the much higher range of WPUA (kg/km^2).

3.3.2. Length frequency

The length frequency distributions between catches of lights on versus lights off were significantly different for ***T. declivis*** (KS test, D-value= 0.4341, p-value < 0.001) (Figure 11) and ***P. melbournensis*** (KS test, D-value= 0.1271, p-value= 0.007) (Figure 12). There was no significant difference for *N. richardsoni* (KS test, D-value= 0.2945, p-value = 0.096) (Figure 13), *P. bassensis* (KS test, D-value= 0.2557, p-value = 0.339) (Figure 14), ***S. flindersi*** (KS test, D-value= 0.214, p-value = 0.469) (Figure 15), *T. degeni* (KS test, D-value= 0.1962, p-value = 0.777) (Figure 16), *L. gallus* (KS test, D-value= 0.3, p-value= 0.541) (Figure 17) and *L. mulhulli* (KS test, D-value= 0.0768, p-value=0.059) (Figure 18). *Trachurus declivis*, ***P. melbournensis*** and *L. mulhulli* displayed normal distributions. *Neoplatycephalus richardsoni*, *P. bassensis*, ***S. flindersi***, *T. degeni*, *L. gallus* all had non-normal distributions across all cruises.

The mean size of fish was significantly reduced with the use of light for *T. declivis* (t = 6.77, df = 1110, p < 0.001) and *P. melbournensis* (t = 2.50, df = 859, p = 0.012) (Table 5). The mean size of fish was significantly increased with the use of light for *L. mulhulli* (t = -4.17, df = 1222, p < 0.001). There was no significant difference for the remaining species: *N. richardsonii* (t = 1.35, df = 81, p = 0.182); P. bassensis (t = 1.96, df = 102, p = 0.052); *S.*

flindersi (t = 1.35, df = 120, p = 0.178); and *T. degeni* (t = -0.087, df = 44, p = 0.931); *L. gallus* (t = 1.25, df = 33, p = 0.219).

Table 5: Mean, min and max length for each of the eight species caught with lights on versus lights off, for catches combined. The asterisk denotes species that had significantly different mean sizes.

	Lights Off				Lights On			
Species	n	Min	Mean ± SD	Max	n	Min	Mean ± SD	Max
N. richardsoni	58	170	310 ± 81	490	25	170	284 ± 82	480
P. bassensis	88	150	322 ± 49	470	16	135	294 ± 71	375
T. declivis *	1037	210	263 ± 14	340	75	165	252 ± 18	294
S. flindersi	104	200	246 ± 22	295	18	200	238 ± 23	287
T. degeni	26	60	149 ± 31	193	20	70	150 ± 33	235
P. melbournensis *	620	100	150 ± 17	236	241	65	146 ± 22	192
L. gallus	25	100	123 ± 12	144	11	80	127 ± 41	239
*L. mulhulli**	516	89	166 ± 21	255	708	90	170 ± 15	233

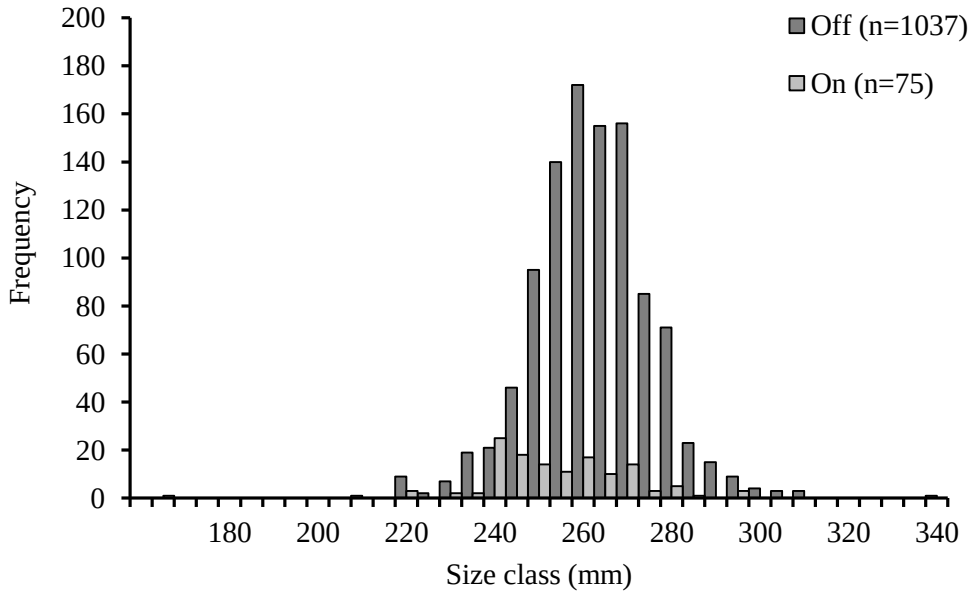

Figure 11: Length frequency distributions of *T. declivis* caught with lights on versus off. Total sample sizes are denoted by *n*.

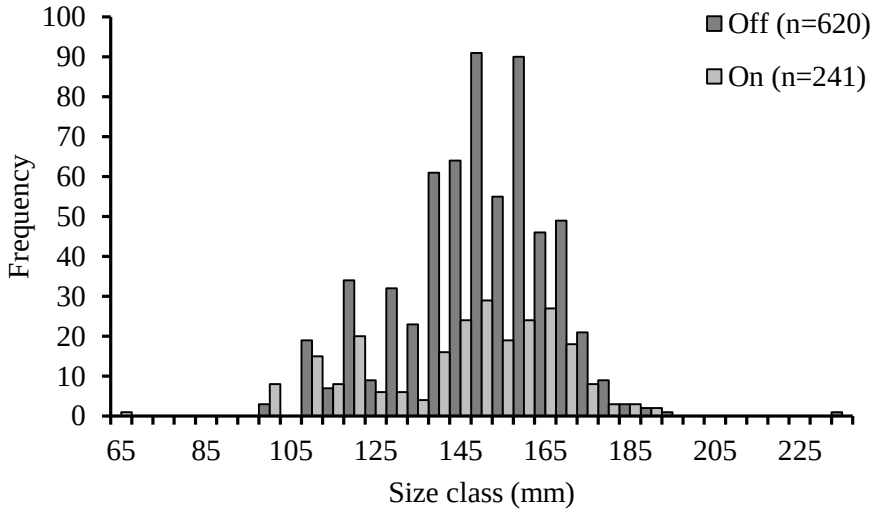

Figure 12: Length frequency distributions of *P. melbournensis* caught with lights on versus off. Total sample sizes are denoted by *n*.

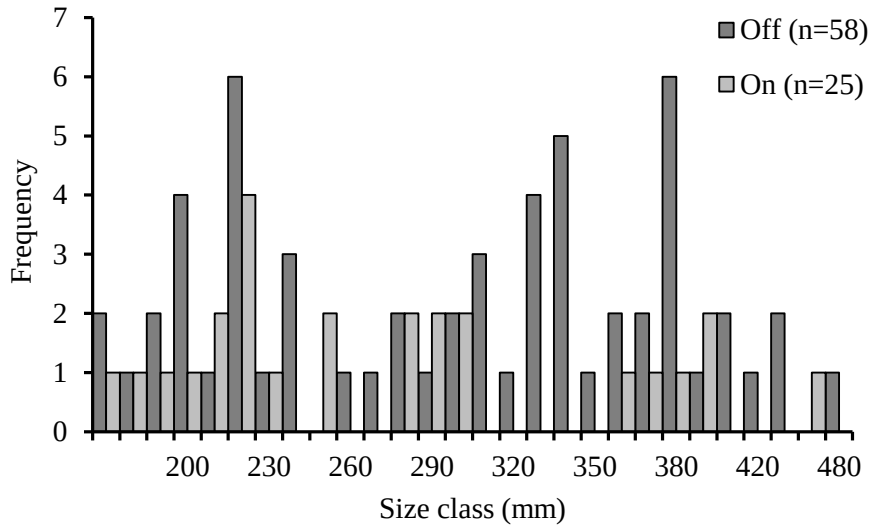

Figure 13: Length frequency distributions of *N. richardsoni* caught with lights on versus off. Total sample sizes are denoted by *n*.

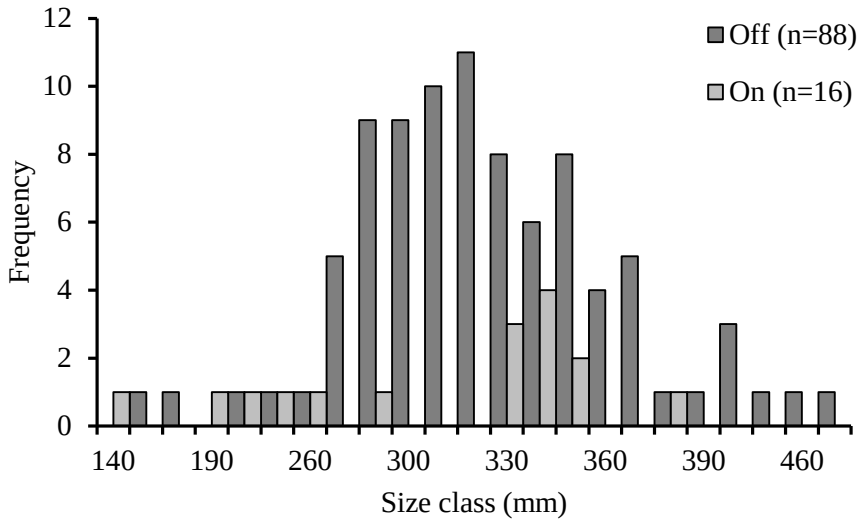

Figure 14: Length frequency distributions of *P. bassensis* caught with lights on versus off. Total sample sizes are denoted by *n*.

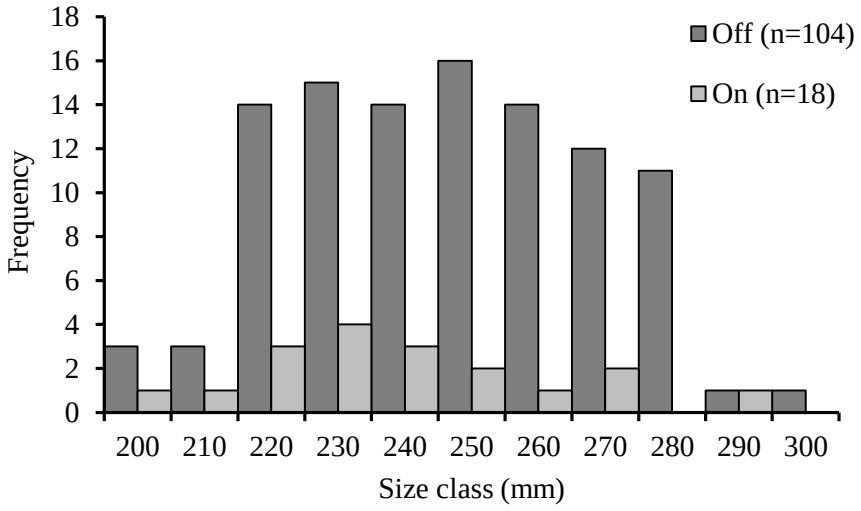

Figure 15: Length frequency distributions of *S. flindersi* caught with lights on versus off. Total sample sizes are denoted by *n*.

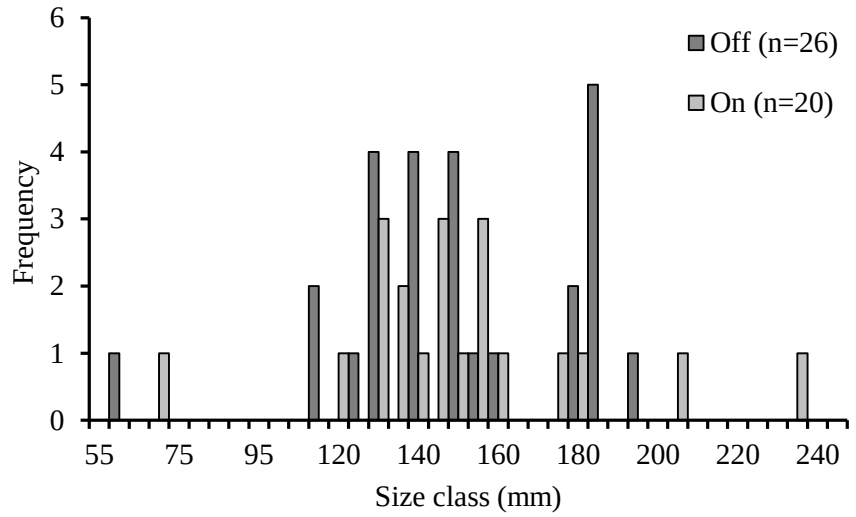

Figure 16: Length frequency distributions of *T. degeni* caught with lights on versus off. Total sample sizes are denoted by *n*.

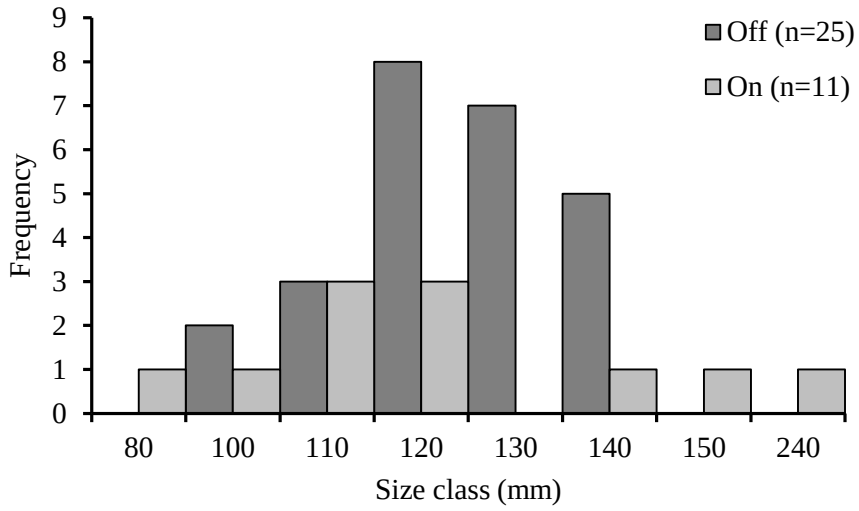

Figure 17: Length frequency distributions of *L. gallus* caught with lights on versus off. Total sample sizes are denoted by *n*.

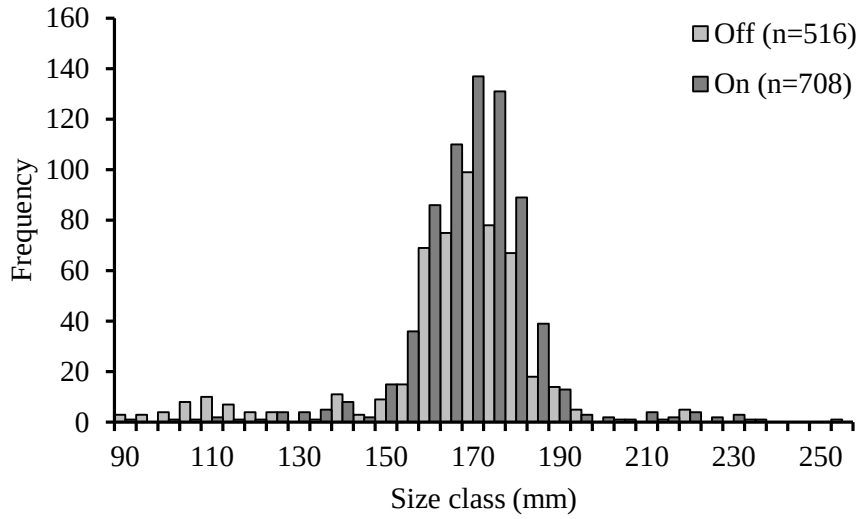

Figure 18: Length frequency distributions of *L. mulhulli* caught with lights on versus off. Total sample sizes are denoted by *n*.

3.4. Discussion

3.4.1. Total fish catch

Overall, the total fish bycatch was reduced by 50% when using lights on trawls, which is contrary to a similar study conducted in temperate waters of the English Channel, near Plymouth, where there was no significant difference (Clarke *et al.* 1986). The system used in the study conducted by Clarke et al (1986) included two 70 W underwater electric lamps. Out of all the fish caught in that study, 54% of the fish was caught without the use of artificial light and 46% were caught with its use (Clarke *et al.* 1986). It is expected that the overall catch would decrease as the theory is that increasing the visual warning in front of the trawl net allows for earlier detection and time for the individual to escape. Another, more recent study looked at the effect of light on the fish being observed in a survey trawl that uses cameras to record fish response (Weinberg and Munro 1999). This system utilized one 50 W quartz halogen lamp. Although the authors did not analyse the effects on total catch they found that there was no significant effect on 5 out of the 6 species. The only other study relating to the use of artificial light on a trawl net was conducted in deep water (up to 1500m) near Madeira and as such it is not comparable (Clarke and Pascoe 1985). In that study, the total volume of fish was increased by up to 79% when using artificial light (Clarke and Pascoe 1985), probably due to the much greater depths that the study was conducted at. Post-hoc power analysis revealed that the sample size in this study produced statistical powers of 0.94 and 0.96 for WPUA (weight) and NPUA (numbers), respectively.

3.4.2. Individual species

The impact of lights on catch rates is species specific. This is a similar result to the few other studies that have examined the use of light on trawl nets. There has only been one other study that was conducted in shallow temperate waters such as those around Tasmania's coast (Clarke *et al.* 1986). Included in that study are species that are similar or related to some of the species examined in this chapter.

Sillago flindersi, P. melbournensis, and the two Platycephalidae species, all had various levels of reduction in catch for both weight and number. It is interesting to note that the two flathead species had different reactions to the light BRD. *Neoplatycephalus richardsoni* had a greater decrease in the number of fish (75 %) than weight (66 %) while *P. bassensis* had a greater reduction in weight (72 %) than in catch numbers (68 %). Both of these species were

considered to be caught in sufficient sample sizes and as such the slight differences observed in this study could be related to any differences in the species morphology, physiology or behaviour. There were no results for species similar to ***S. flindersi***, and ***P. melbournensis*** and the flathead species to be used for comparison.

The other species of interest were found to be not statistically significant, and this is likely to be due to the high degree of catch variability between tows. For the interest of comparison, however, these species will be compared to the literature. In this study, the *Trachurus* species, ***T. declivis***, exhibited a 93 % decrease in weight and 88 % decrease in numbers. In a related study, another Carangidae species, *Trachurus trachurus*, was found to increase by 200 % and 146 % for weight and numbers, respectively (Clarke *et al.* 1986). Considering the similarity of these two species in terms of size, shape and geographical distribution (Froese and Pauly 2014) it is not expected that they should have opposite effects with the use of artificial light on the trawl. Since they are also both schooling species it would be expected that any change exhibited will happen in large numbers. It is hypothesised that, unlike what was seen in this study, it is more likely a schooling species such as mackerel will increase in catch with the use of light as they are more likely to be herded (Ramm and Xiao 1995). The increased visual warning of the lights will illuminate not only the trawl but also the trawl board and warps that are used to produce a sand cloud acting as a barrier (Radakov 1971).

The Triglidae species in this study (*L. mulhulli*), although not found to be significant, was increased by 15 % in terms of weight and 12 % in terms of numbers when using an artificial light. There have been two related species that have been studied for the reaction to light, *Eutrigla gurnardus* and *Aspitrigla cuculus* (Clarke *et al.* 1986). It was found that *E. gurnardus* was decreased by 31 % and 34 %, while *A. cuculus* was decreased by 24 % and 21 %, for weight and numbers, respectively. Once again, these species are quite similar in terms of morphology and habitat but grow to different maximum lengths and are distributed to different depths which could be a reason for the difference seen (Froese and Pauly 2014). *Lepidotrigla mulhulli* is the smallest of the three species and found in the shallowest waters. This may influence the effectiveness of the light BRD on their catch rates because they are adapted to different light conditions.

In this study, the representative flatfish, *L. gallus*, was increased in terms of catch weight by 15 % but decreased by 55 % in terms of its numbers. This means that although there were less fish caught of this species, the mean size of each fish was bigger when captured with

light. This is not expected as it is more likely that that there would be a decrease in the mean size of fish. This is because a larger fish is more likely to escape due to the greater swimming abilities. In the context of this study, however, it is more likely that the sample sizes of this species were too small in each shot to provide meaningful conclusions. This was not seen in similar Pleuronectidae spp such as *Limanda limanda, Pleuronectes platessa* and *Microstomus kitt* (Clarke *et al.* 1986). The catch weight of *L. limanda, P. platessa* and *M. kitt* decreased by 23 %, 17 % and 50 %, respectively. The decrease in catch numbers for *L. limanda* and *P. platessa* were 19 % and 27 %. These species are not related directly to *L. gallus* but instead they all come under the Pleuronectidae family. As such there are differences in morphology, distribution and habitat of these four species (Froese and Pauly 2014). It has been demonstrated by Ryer and Barnett (2006) that in the absence of light, flatfish are less likely to have an ordered directional reaction to an oncoming trawl. This is in line with the theory that vision is the most important sense during interactions with fishing gears (Glass and Wardle 1989; Walsh and Hickey 1993; Wardle 1993).

It is acknlowledged that the lights system used in this study may not be comparable to those used in previous studies. However, with the lack of literature in this area comparison has still been tentatively made. There were no results for species similar to *T. degeni* with which to compare. *Thamnaconus degeni* displayed an increase in catch weight and no difference in numbers suggesting the only effect that the light BRD had on this species is to catch larger individuals.

3.4.3. Length frequencies

T. declivis, *P. bassensis* and *L. mulhulli* had normally distributed size frequency distributions. For *L. gallus* and *T. degeni*, there is evidence that the distribution could also be normally distributed however, with such low sample sizes it is not as obvious as the species mentioned above. A bimodal length frequency distribution for ***P. melbournensis*** and *N. richardsoni* possibly indicates that the trawl encountered two cohorts within sampling trips. Lastly there is the distribution of ***S. flindersi*** which had a uniform distribution. There was almost an equal number of fish across the observed size range.

The length frequency distributions were only significantly different for two of the eight species of interest. These were ***T. declivis*** and ***P. melbournensis***. Both species had normal distributions but it was found that the average size of ***T. declivis*** was reduced from 263 mm to 254 mm and ***P. melbournensis*** was reduced from 150 mm to 146 mm. However it must be

considered whether this significance is biologically relevant since these are only changes of 9 mm and 4 mm, for ***T. declivis*** and ***P. melbournensis*** respectively. Alternatively it was found that, although non-significant, the mean size of *P. bassensis* and *N. richardsoni* was reduced by 28 and 26 mm respectively. It is likely that the small sample size made this difference statistically undetectable.

Only two other papers that examined the use of light in trawl nets have presented length frequency results. Weinberg and Munro (1999) looked at the effect of artificial light on 6 fish species and their ability to escape beneath a survey trawl. It was found that length did not have an effect on catch rates of each species. Although mean sizes are provided, there was no statistical analyses of the differences in lengths of fish between lit and unlit trawls. Hannah *et al.* (2015) looked at the effect of light on echelon species (*Thaleichthys pacificus*) and found that larger individuals were more likely to escape with the use of light in a trawl net.

The reductions in mean size of fish seen in this chapter are to be expected as size is a factor in the swimming speed and visual capabilities of a fish. A smaller fish will be slower due to its smaller fins and muscles that can be used to propel its body (Beamish 1978). In this instance, a side effect of using the lights as a bycatch reduction device would be having, in general, smaller fish.

3.4.4. Concept of light

Results from this study and the few related studies indicate that different species react differently to the use of artificial light when trawling. The reasons for these differences could be due to the physiological variations between different species. For a fish to utilise an increased visual warning, then its greatest chances of escaping are with the optimal swimming and visual capabilities. The visual capabilities allow it to detect the oncoming trawl and the swimming ability is used for avoidance.

Two main factors that must be considered in the effectiveness of the use of this device include the moon light and the time of night (Johnsen and Iilende 2007; Lowry *et al.* 2007; Yousif 2003; Zimecki 2006). They may reduce the impact of the artificial light with the introduction of ambient light. It may also be due to the altered behaviours of the species that are encountered. Just as the prawns are likely to migrate when there is a full moon, some fish species may be more or less inclined to hide. For example, Lowry *et al.* (2007) looked at the catch rates of gamefish such as black marlin (*Makaira indica*), dolphin fish (*Coryphaena*

hippurus), and yellowfin tuna (*Thunnus albacares*) and found a significant relationship between moon phase and catch-per-unit-effort (CPUE). It can also be seen in pole-and-line fisheries where by baitfish are captured using artificial light and a stick-held dip net. The catch rates of the baitfish are most influenced by the lunar cycle (Lewis 1990) and during the full moon, when the fish are less attracted to the lights, more hauls are needed (Nichols and Rawlinson 1990). These factors were unable to be testing in this study due to the limited trawling time across entire nights and moon phases.

With more extensive trials, the concept of light as a BRD could be developed for commercial prawn trawl fisheries that could improve the sustainability of their practices. For some fisheries the ratio of fish to prawns is as much as 10:1 (Courtney *et al.* 2006). By using artificial light on the headline of the trawls, this ratio could be reduced by half based on the results seen in this study. Benefits of reducing such large amounts of fish bycatch range from reducing environmental impact to increasing the quality of prawns. The applicability of such a device will need to be tested in other locations and fisheries. For example the effect of the light was not as strong in the shallow tropical waters of the Queensland coast (see Chapter 2). More rigorous testing will need to be carried out, however, it is apparent that the variations between location will alter the effectiveness of this device. Such things as the water clarity, depth, temperature and salinity may all impact and the most important thing is the difference in the species encountered. Tropical species have different physiologies and life histories to those species of temperate waters. Therefore, it may need to be taken into account that fish species in tropical waters may behave different.

3.4.5. Conclusion

This study demonstrates that using artificial light changes the catch rate of certain fish species from trawls in North-Eastern Tasmania. The LED light BRD used in this study halved overall fish catch in terms of weight and reduced numbers by 40%. Individual species had different catch rates with the use of light, including some species that increased in catch. This shows the need to study the factors that allow a species to detect and avoid an oncoming trawl and how these variables affect catch rates. It was suggested by Clarke *et al.* (1986) that the reason for these differences (such as morphological, physiological and behavioural) should be studied to explain such differences. It is proposed that the vision is the main indicator of a fish's ability to detect an oncoming trawl, while the maximum swimming speed is an indicator of the fish's ability to avoid it. Both of these are presented in the following chapters.

It is also acknowledged that future studies need an experimental design with replication during different moon phases to test effectiveness of the light BRD in different ambient light intensities.

3.5. References

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3.6. Appendices

Appendix 3.6.1: Station log data for each shot during each of the three cruises.

			Start coordinates		End coordinates					
Cruise	Shot	Trawl duration (mins)	Latitude	Longitude	Latitude	Longitude	Area trawled (km^2)	Trawl speed (knots over ground)	Mean Depth (m)	Light status
June	1	45	-40.3448	148.5562	-40.3061	148.5571	0.0301	3.4	30.0	Off
	2	45	-40.3016	148.5553	-40.3403	148.5483	0.0304	3.1	30.5	On
	3	45	-40.3393	148.5441	-40.304	148.5551	0.0282	3.1	31.7	On
	4	45	-40.3113	148.5629	-40.3491	148.5562	0.0297	3.1	30.5	Off
May	1	45	-40.3079	148.5578	-40.3489	148.5535	0.0320	3.3	34.1	Off
	2	45	-40.3503	148.5547	-40.3075	148.5635	0.0337	3.4	33.8	On
	3	30	-40.3148	148.5568	-40.3561	148.5389	0.0339	4.1	29.7	On
	4	45	-40.3569	148.5349	-40.3221	148.5576	0.0303	3.5	30.1	Off
	5	45	-40.3033	148.5587	-40.3434	148.5414	0.0329	3.5	34.1	On
	6	45	-40.3465	148.5482	-40.3134	148.5482	0.0258	3.0	29.9	Off
	7	45	-40.3109	148.5469	-40.3466	148.5365	0.0285	3.8	29.9	Off
	8	45	-40.3459	148.5369	-40.3161	148.5398	0.0233	2.8	34.1	On
Nov	1	45	-41.0195	148.3638	-41.057	148.3353	0.0337	3.5	39.9	On
	2	45	-41.0533	148.3184	-41.0152	148.3616	0.0390	3.5	37.7	Off
	3	30	-41.0165	148.3592	-41.0515	148.333	0.0312	3.5	36.6	Off
	4	45	-41.0458	148.3346	-41.0092	148.3619	0.0327	3.5	35.0	On
	5	45	-41.0169	148.365	-41.056	148.3382	0.0343	3.5	40.4	Off
	6	45	-41.0566	148.3364	-41.02	148.3571	0.0310	3.5	38.6	On
	7	45	-41.0196	148.3554	-41.0575	148.3299	0.0331	3.5	36.4	On
	8	45	-41.0578	148.3505	-41.019	148.3601	0.0307	3.5	38.5	Off
	9	45	-41.0194	148.3617	-41.0589	148.3327	0.0352	3.5	39.8	On

	10	45	-41.0583	148.3324	-41.0219	148.3562	0.0316	3.5	38.5	Off
	11	45	-41.0205	148.3589	-41.0551	148.3352	0.0303	3.5	38.8	Off
	12	46	-41.0542	148.3377	-41.0136	148.3679	0.0362	3.5	39.8	On

Appendix 3.6.2: Design of lights

The development of the light BRD started with a project initiated by the AMC and funded by National Heritage Trust in 2008. The light design is available in the report by Gaston (2008). The same design was used again in a study done by Maynard and Gaston (2010). The lights were designed with the eventual use in the commercial industry in mind and as such the following design requirements were used to guide the design of the (prototype) lights:

1. Rugged to withstand operating on a commercial vessel, salt water conditions, weather and the trawling process.
2. Restricted access to internal components.
3. Easily rechargeable with batteries located within each unit.
4. Able to operate at depths down to 500 m.
5. Forward facing light orientation only
6. Simple yet secure attachment to the net headline.
7. Lights able to remain on for 12 hours of continuous trawling.
8. The size of each unit needs to be small enough so as to not impact on regular trawling operations.
9. The device must be neutral or positively buoyant as so to minimise the chance of dragging on the headline.
10. The price of each must be reasonable in the context of commercial aspirations and to be easily replaceable if a unit is lost.

The updated design had aluminium housings and was 19 cm long and 2 kg in weight (Figure 1, Figure 2 and Figure 3). The internal components were set in an electrical hypoxy resin (SmoothOn PMC-780 polyurethane elastomer[1]). A loop at the head of the unit allows for easy attachment to the headline with a shackle. Each light was activated by plugging in an 'active' dongle into the rear of the unit. The specifications of the output of light are detailed in Table 1.

[1] Barnes F-190 polyurethane elastomer was tried but did not work.

Table 1: Specifications of the output of light for the light BRD.

Specification	Unit
Power	9 Watts
Correlated Colour Temperature	5000 Kelvin
Beam Angle	100 Degrees
Lumens Output	660 Lumens
Luminous Flux	660 Lux
Headline Spacing	3 Metre (between each unit)*

* This is to ensure overlapping beams of light.

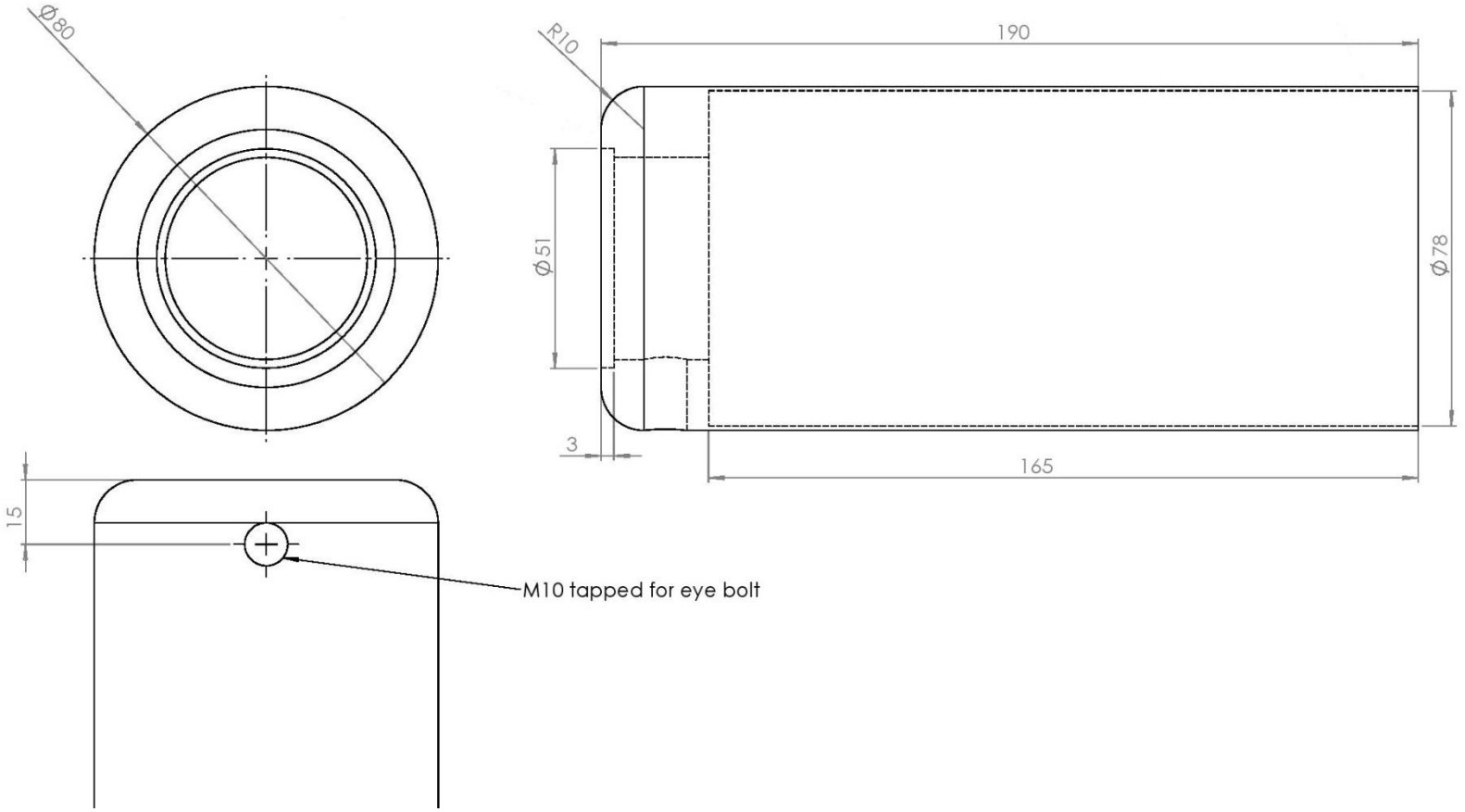

Figure 1: Drawing of the final version of the housing for the light BRD. Clockwise from top left are the front, side, and top views (diagrams provided by Energy Options International).

Appendix 3.6.3: Mean WPUA (kg/km^2) and NPUA (number/km^2) of all species caught for all tows with lights on versus lights off.

				WPUA (wgt/km^2)		NPUA (no./km^2)	
Group	Common Name	Scientific Name	n	off	on	off	on
Cephalopod	Arrow squid	*Nototodarus gouldi*	3	77.2	4.3	816.8	28.4
	Calamari	*Sepioteuthis australis*	20	60.1	35.2	688.2	377.1
	Cuttlefish	*Sepia spp.*	8	5.3	1.3	189.5	63.0
	Octopus	*Octopus pallidus*	17	19.6	11.1	56.6	48.3
	Squid	Teuthida spp.	3	13.5	8.6	29.4	128.7
Crustacean	Surf crab	*Ovalipes australiensis*	1	0.3		33.0	
	Balmain bug	*Ibacus peronii*	12	27.0	8.3	262.1	67.8
	Crabs	*Pilumnidae spp.*	2		1.1		36.3
	Hermit Crab	*Diogenidae spp.*	2	1.7	7.7	66.0	42.9
	Prawn	*Penaeus spp.*	5	0.1	0.5	47.9	30.0
	Spider Crab	*Majidae spp.*	4	4.5	8.5	49.8	34.2
Other	Assorted molluscs	Bivalvia	15	96.4	36.6	542.1	814.4
Sharks and Rays	Angel shark	*Squetina tergocellata*	6	16.3	42.5	44.1	59.1
	Banded stingaree	*Urolophus cruciatus*	23	99.7	38.6	410.5	155.1
	Draughtboard shark	*Cephaloscyllium laticeps*	17	106.9	54.3	109.1	44.0
	Elephantfish	*Callorhynchus milii*	2	110.3		48.8	
	Melbourne skate	*Raja whitleyi*	1	639.7		33.7	
	Numbfish	*Narcine tasmaniensis*	23	43.1	40.9	238.5	159.4
	Peacock skate	*Pavoraja nitida*	2	35.9		50.2	
	Sandyback skate	*Urolophus bucculentus*	9	83.3	103.1	45.4	30.8
	Sawshark	*Pristiophorus nudipinnis*	2	32.5		36.2	

	Skate	*Raja spp.*	1	203.5		35.1	
	Sparsely spotted stingaree	*Urolophus paucimaculatus*	25	611.5	247.7	3504.9	1320.8
	Spiny dog shark	*Squalus acanthiusa & S. megalops*	4	4.7	2.8	50.7	55.2
Teleost	Banded sole	*Zebrias scalaris*	3	5.7		35.1	
	Barracouta	*Thyrsites atun*	11	10.9	11.2	93.8	55.8
	Beaked salmon	*Gonorynchus greyi*	1		1.5		30.4
	Blue warehou	*Seriolella brama*	6	74.1	12.2	278.4	45.7
	Boarfish	*Pentaceropsis recurvirostris*	2	7.6		34.0	
	Bullseye	*Pempheris sp.*	5	1.2	24.3	113.3	260.2
	Common gurnard perch	*Neosebastes scorpaenoides*	18	67.3	38.1	130.5	79.3
	Crested flounder	*Lophonectes gallus*	21	2.8	4.3	209.0	125.7
	Deepwater ocean perch	*Helicolenus percoides*	1		1.6		32.2
	Degen's leatherjacket	*Thamnaconus degeni*	24	17.8	15.3	605.1	486.0
	Eastern school whiting	*Sillago flindersi*	12	112.7	51.0	924.0	396.7
	Globefish	*Contusus richei*	7	36.7	21.2	136.3	78.2
	Goatfish	*Upeneichtys vlamingii*	10	10.5	11.2	97.5	53.1
	Golden roughy	*Aulotrachichthys pulsator*	10	2.5	3.1	0.6	0.3
	Greenback flounder	*Rhombosolea tapirina*	3	16.8	20.9	0.2	0.3
	Grooved gurnard	*Lepidotrigla modesta*	11	16.8	20.0	1.8	1.3
	Gurnard	*Triglidae spp.*	3	159.3	22.3	1.940	0.208
	Happy moment	*Maxillicosta whitleyi*	15	5.5	0.7	2.005	0.304
	Jack mackerel	*Trachurus declivis*	24	382.4	38.5	17.627	2.371
	Kumu	*Chelidonichthys kumu*	24	89.7	77.7	6.479	5.056
	Mosaic cowfish	*Aracana ornata*	7	3.5	8.8	34.5	89.2
	Pike	*Dinolestes lewini or Sphyraena novaehollandiae*	13	21.6	36.4	157.5	283.1
	Porcipine fish	*Diodon nicthemerus*	24	64.8	67.9	128.5	105.6
	Redbait	*Emmelichthys nitidus*	5	10.9	4.5	131.9	89.0

	Roundsnout gurnard	*Lepidotrigla mulhalli*	25	111.4	117.7	1717.8	1776.8
	Sand flathead	*Platycephalus bassensis*	19	80.9	46.7	301.4	128.5
	Shaws cowfish	*Aracana aurita*	23	40.5	43.5	213.5	223.6
	Silver biddy	*Parequula melbournensis*	24	102.8	33.3	2103.2	680.1
	Silver trevally	*Pseudocaranx dentex*	1		0.3		29.7
	Slimy mackerel	*Scomber australasicus*	1		4.8		32.3
	Spiny gurnard	*Chelidonichthys spinosus*	22	17.1	17.5	311.4	364.5
	Spotted Mackerel	*Scomberomorus munroi*	1		5.9		59.3
	Stargazer	*Kathetostoma laeve*	9	65.4	6.6	98.2	29.5
	Stinkfish	*Foetorepus calauropomus*	25	117.1	27.2	1330.0	216.3
	Surf fish	*Iso rhothophilus*	4	1.2	1.6	52.5	32.3
	Swallowtail	*Centroberyx lineatus*	9	2.4	2.5	162.8	244.3
	Tiger flathead	*Neoplatycephalus richardsoni*	23	73.1	22.6	264.2	92.4

CHAPTER 4: Investigating photoreceptor densities, potential visual acuity, and cone mosaics of shallow water, temperate fish species

4.1. Introduction

Most fish that inhabit shallow waters can detect colours and patterns with well-developed eyes (Gurthrie and Muntz 1993a). Pigments (rhodopsin and porphyropsin) in the photoreceptors absorb different light wavelengths and are stimulated at different light intensities (Fernald 1988). This means that fish can have both photopic vision (well-lit, colour) that is mediated by cones, and scotopic vision (low-light) that is mediated by rods (Fernald 1988). The arrangement of single, double and sometimes triple cones in the retina is known as the mosaic, and is adapted to the habitats and behaviour of a species (Evans and Browman 2004; Lyall 1957; Raymond *et al.* 1995). Likewise, the amount of rod and cone photoreceptor cell types in the retina is related to the habitat of the particular species. It has been well documented, for example, that those species living in shallow waters often have a greater selection of cones than deep-water species that are predominantly in the dark (Mas-Riera 1991; Pankhurst 1987).

In addition to the detection of certain wavelengths and light intensities, fish also need to be able to resolve an image. The photoreceptor cells are involved in potential visual acuity whereby the resolving power of the eye is a function of photoreceptor cell spacing (in particular the cones) and the lens size (Tamura 1957). Potential visual acuity is used to describe the fish's ability to detect fine detail and is important for shape discrimination (Douglas and Djamgoz 1990). Some species require greater potential visual acuity to be able to discriminate between a range of visual stimuli. This includes objects in the surrounding habitat and places to hide or the shapes of other species that are considered predators (Lythgoe 1968). Potential visual acuity is a useful measure to compare the visual capabilities of fish, especially in response to human activities such as aquaculture and fisheries. The behaviour of fish in response to light is used for sampling and ecological observations (Catalan *et al.* 2014). Likewise, it has been hypothesised that fish with higher potential visual acuity and/or sensitivity to light could be attracted to, or stimulated to avoid, illuminated trawl fishing gear. However, it is critical to describe the visual function of species that may interact with fishing gear, in order to interpret or predict their behavioural response.

In the last chapter, the effect of artificial light on the capture of a selection of shallow water teleost species in North-Eastern Tasmanian coastal waters was presented. The next step is to quantify the visual capacity of these same species. For all but one of these species, *Trachurus declivis*, there is no literature that has quantified the photoreceptor cells and potential visual

acuity; nor provides the cone mosaic patterns. The aim of the study was to quantify the photoreceptor cell densities and potential visual acuity as well as describe the cone mosaic and general eye dimensions. This information will further enhance the interpretation of the response of fish to bycatch reduction devices, specifically those using light.

4.2. Materials and Methods

4.2.1. Eye sample collection

Fish samples were collected with a demersal fish trawl in North-Eastern Tasmania. The trawl net measured 16 m in headline length and was designed to sweep an 11 – 13 m wide strip of the seabed. It was towed at 3 knots by a 35 m fisheries training vessel, the *FTV Bluefin*. The headline was 2.3 m above the seabed. Trawling was conducted during the night at 30 m depth starting at the following coordinates: 40°18”828’S and 148°32”646’E.

The left eyes of five fish were collected from each of eight species: roundsnout gurnard *Lepidotrigla mulhalli*; crested flounder *Lophonectes gallus*; sand flathead *Platycephalus bassensis*; eastern school whiting *Sillago flindersi*; tiger flathead *Neoplatycephalus richardsoni*; Degen’s leatherjacket *Thamnaconus degeni*; silver biddy *Parequula melbournensis*; and jack mackerel *Trachurus declivis*.

The fish length, eye and lens diameters were measured with callipers to the nearest 1 mm. Eyes were dissected and after inspection of eye quality (i.e. absence of corneal/lenticular opacity, pupil atrophy, and inflammation), a small incision was made to maximise infiltration of the fixative and to retain orientation. Samples were fixed for 24 h in 5% glutaraldehyde in a sucrose-phosphate buffer, and then stored in 70% ethanol. The eyes were dissected to remove the retina just prior to analysis.

4.2.2. Histology and retinal morphology

Retinal samples were manually dehydrated to 100% ethanol and embedded using a JB4 resin histology kit (JB4, Agar Scientific Ltd, UK). Retinas were halved to form dorsal and ventral areas. Ten random transverse sections (3 µm thickness) per retinal sample per area were cut with a Microm microtome (Heidelberg HM340) and placed in water drops on a glass slide. They were allowed to dry and sections were stained with Lee’s Methylene Blue-Basic

Fuchsin and mounted in TBS® SHUR/mount toluene-based mounting media with a coverslip. Three 100 µm transects from five sections were randomly chosen and images taken under a light microscope at 400x magnification. The number of photoreceptor (PR) nuclei and cone ellipsoids were counted in each transect. For the purpose of this study, both double and single cones were counted as one (Hajar *et al.* 2008). Cells that overlapped the transect were only counted on the left side. The following formula was used to find the number of rods:

$$Rods = PR\ nuclei - cone\ ellipsoids$$

Cell counts were expressed as density: cells per 0.01 mm^2 (squared counts from 100 µm transects). The only differences between dorsal and ventral cell densities occurred in *L. mulhalli* whereby the density of rods were 1.8 times higher in dorsal than ventral, (t-test, df=8, t=2.86, p-value=0.02); and cones were 1.6 times greater in the dorsal than ventral,(t-test, df=8, t=3.84, p-value = 0.004). They were also different in *P. bassensis* whereby cones were 2 times higher in dorsal than in ventral cells, (t-test, df=8, t-value=4.39, p-value= 0.002). Consequently the cell counts were pooled by region for each of the eight species to enable further comparison.

Tangential sections (3 µm) per species were cut and stained in a similar fashion. From them, the cone mosaic (the pattern of single and double cones) was observed. The tangential sections were also used to measure the diameter of the double cones 'en face' at the widest cross section using *Image J* (Version 1.46r, National Institute of Health, USA). To calculate the minimum separable angle (MSA) (α), the lens diameter and highest density of cones (per 0.01 mm^2) were used in the following equation (based on Tamura 1957):

$$tan\left(\frac{\alpha}{2}\right) = \frac{q(1+s)}{2F}$$

Where, q is the mean distance between two cones in mm ($q = 0.1/\sqrt{p}$); where p is density of cones per unit area 0.01 mm^2), s is the shrinkage factor and F is focal length ($F = m$ x r; where m is Matthiessen's ratio (2.55) and r is lens radius in mm). The shrinkage for each species was calculated from the difference between the eye diameter before and after fixation. Since the majority of individuals (75%, n= 40) across all the species did not display

shrinkage, the shrinkage factor has been omitted from the calculation of α. MSA (α) was used to find the potential visual acuity (VA) according to (Tamura 1957):

$$VA = \left(\alpha \times \frac{180}{\pi} \times 60\right)^{-1}$$

Retinal magnification (β) was calculated using the following:

$$\tan\beta = \frac{1 * (1+s)}{F}$$

Whereby β is the angle subtended by a 1 mm projection on the retina.

4.2.3. Data Analysis

Pearson's correlation was used to measure the linear correlation between: eye diameter and total fish length; and lens diameter and total fish length. An Analysis of Variance (ANOVA) in the statistical package 'R' (version 2.15.3) was used to detect statistical difference between species for the following: cone density, rod density, minimum separable angle and potential visual acuity. Tukeys' post-hoc test was used to find where the difference occurred. Data was accepted as significantly different when $P < 0.05$. Error bars were presented as standard error of the mean calculated.

4.3. Results

4.3.1. Eye and retinal morphology

With the exception of the oval nature of the eyes of *P. bassensis* and *N. richardsoni*, all species had spherical eyes. The species with laterally compressed body shape (including *T. degeni*, *T. declivis*, *L. mulhalli*, *P. melbournensis* and *S. flindersi*) had eyes that were located on either side of the head allowing for greater peripheral vision. In dorso-ventrally compressed fish, such as the *Platycephalus* spp., eyes were orientated dorsally and provide greater binocular vision.

The fish eye sizes ranged from 6.2 ± 1.3 mm (mean ± SD, here and throughout) in the smallest species (*L. gallus*) to 18.4 ± 1.5 mm in the largest (*P. bassensis*) and the mean lens diameter ranged between 2.1 mm ± 0.2 mm (*L. gallus*) and 7.7 mm ± 0.4 (*P. bassensis*) (Table 1).

Table 1: Fish size (length), eye and lens diameters, and cone photoreceptor diameter for the eight species studied from benthic trawls in North-Eastern Tasmania. SC = single cones, DC = double cones.

		Total length (mm)			Eye diameter (mm)	Lens diameter (mm)	Cone diameter (µm)	
Species	*n*	Mean (± SD)	min	max	Mean (± SD)	Mean (± SD)	Mean SC (± SD)	Mean DC (± SD)
L. gallus	5	116.0 (14.6)	100	137	6.2 (1.3)	2.1 (0.2)	6 (0)	11 (1.5)
L. mulhalli	5	171.2 (19.0)	140	190	13.2 (2.1)	5.6 (1.0)	6 (1.1)	16 (0.9)
N. richardsoni	5	326.4 (47.4)	251	371	16.6 (1.9)	7.2 (1.1)	N/A	N/A
P. bassensis	5	375.8 (125.6)	165	470	18.4 (1.5)	7.7 (0.4)	5 (0.6)	12 (1.2)
P. melbournensis	5	162.0 (20.4)	141	192	13.2 (1.9)	5.6 (1.0)	4 (0.5)	8 (0.6)
S. flindersi	5	251.0 (18.8)	235	280	14.4 (0.5)	6.3 (0.4)	11 (0.7)	16 (0.8)
T. declivis	5	211.8 (36.0)	162	262	13.4 (2.3)	5.9 (1.2)	N/A	14 (0.7)
T. degeni	5	131.4 (35.2)	139	170	11.6 (1.1)	4.4 (0.5)	2 (0.5)	8 (0.5)

The increase in eye diameter for each species coincided with the increase in total fish length and was described with linear trendlines (Figure 1). For five out of the eight species there was a significant correlation between the two variables (Table 2). *Thamnaconus degeni* and *S. flindersi* had almost no correlation and *L. mulhalli* could not be used as it only had two data points.

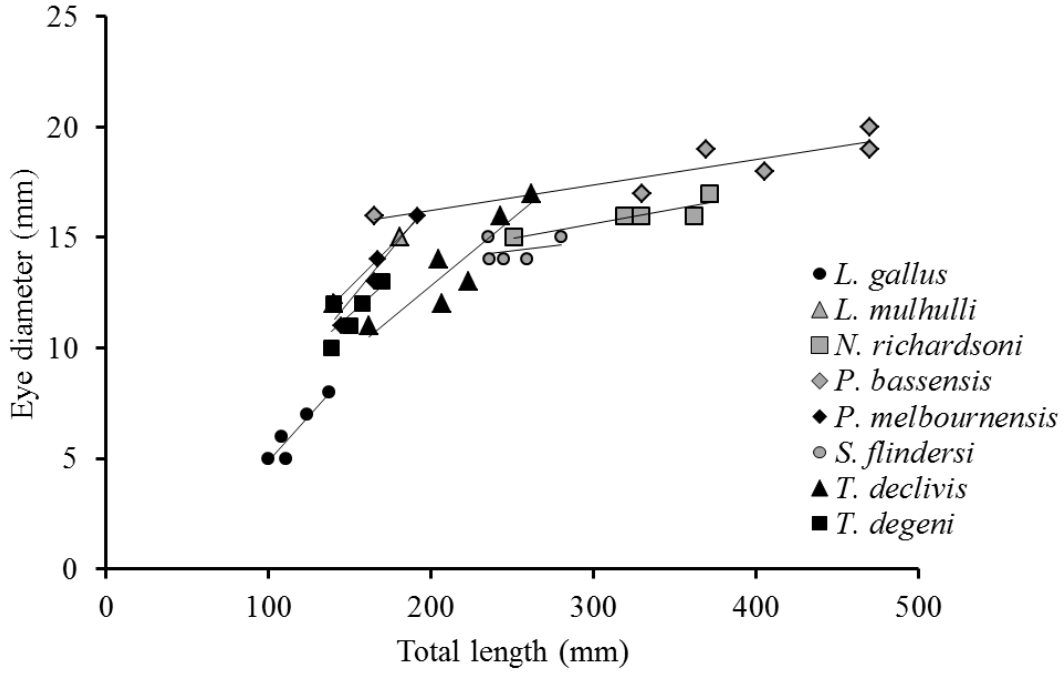

Figure 1: Eye diameter (mm) and total fish length (mm) of eight species studied from benthic trawls in North-Eastern Tasmania.

Table 2: t-value, degrees of freedom (df), p-value and r^2 for Pearson's correlation between eye diameter (mm) and total fish length (mm) of eight species studied from benthic trawls in North-Eastern Tasmania.

Species	t-value	df	p-value	r^2
L. gallus	4.52	3	0.020	0.93
L. mulhalli	N/A	1	N/A	N/A
N. richardsoni	3.46	3	0.041	0.89
S. flindersi	0.57	3	0.606	0.31
P. bassensis	4.03	4	0.016	0.89
P. melbournensis	5.63	3	0.011	0.95
T. declivis	4.43	4	0.011	0.91
T. degeni	2.01	3	0.139	0.75

Similarly, linear correlations show the trend between lens diameter and total length (Figure 2). Lens diameter increased with increasing length of the fish for six out of the eight species (Table 3). Only half of the species, *P. bassensis* , *P. melbournensis* , *L. mulhalli, and S. flindersi,* were found to have a significant correlation.

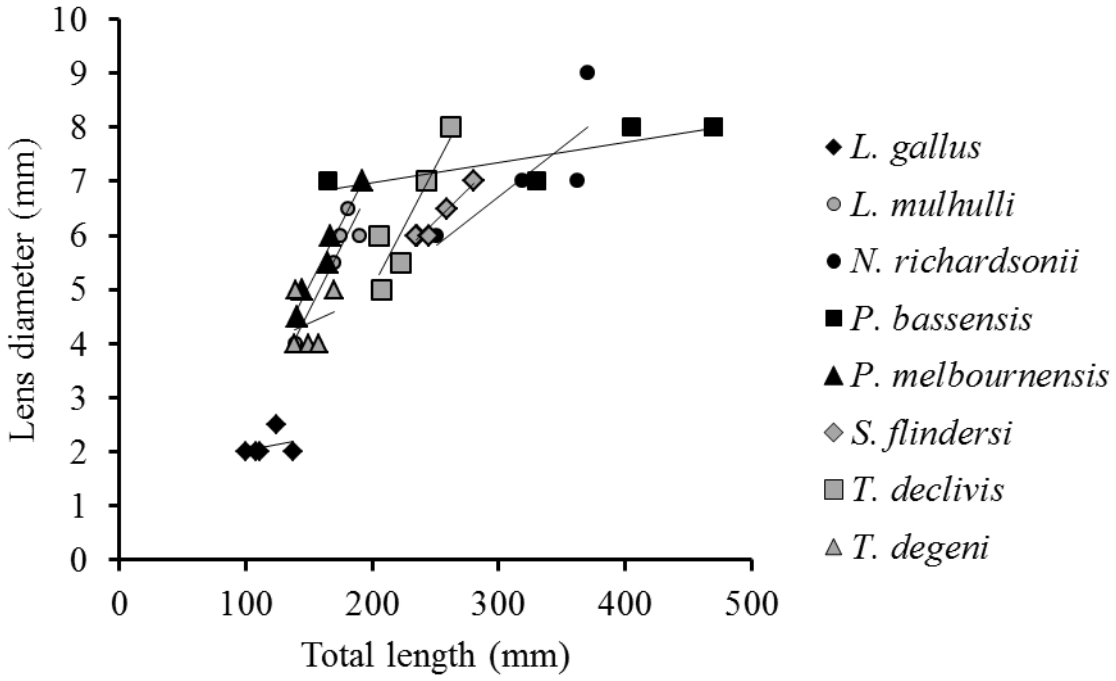

Figure 2: Lens diameter (mm) and total fish length (mm) of eight species studied from benthic trawls in North-Eastern Tasmania.

Table 3: t-value, degrees of freedom (df), p-value and r^2 for Pearson's correlation between lens diameter (mm) and total fish length (mm) of eight species studied from benthic trawls in North-Eastern Tasmania.

Species	t-value	df	p-value	r^2
L. gallus	0.56	3	0.616	0.31
L. mulhalli	4.40	3	0.022	0.93
N. richardsoni	2.24	3	0.110	0.79
P. bassensis	3.38	4	0.027	0.86
P. melbournensis	8.84	3	0.003	0.98
S. flindersi	8.19	3	0.004	0.98
T. declivis	3.30	4	0.298	0.85
T. degeni	0.45	3	0.681	0.25

4.3.2. Rod density

The mean density of rods (cells per 0.01 mm^2) was significantly different across the eight different species (ANOVA, $F_{7,72}$= 12.72, P<0.001) (Figure 3). *Lepidotrigla mulhalli* had the lowest density of rods with 22 800 ± 2 980 per 0.01 mm^2. There was a central group, consisting of *P. bassensis, L. gallus, P. melbournensis* and *S. flindersi*, with rod densities that ranged from 41 670 to 52 220 rods per 0.01 mm^2. The highest rod density of 76 630 ± 5 876 cells per 0.01 mm^2 was in *T. declivis*. Photoreceptor cells can be seen in Figure 4.

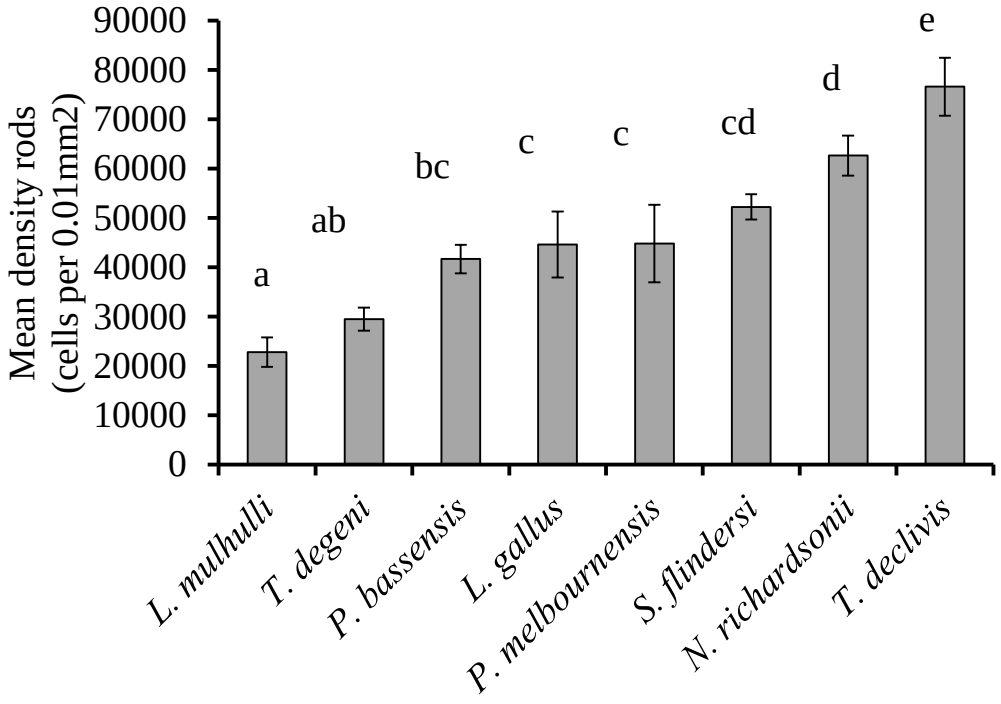

Figure 3: Mean number of rods (cells per 0.01 mm^2) ± SE, in eight different teleost species studied from benthic trawls in North-Eastern Tasmania. Common letters represent values that are not significantly different.

4.3.3. Cone density and diameter

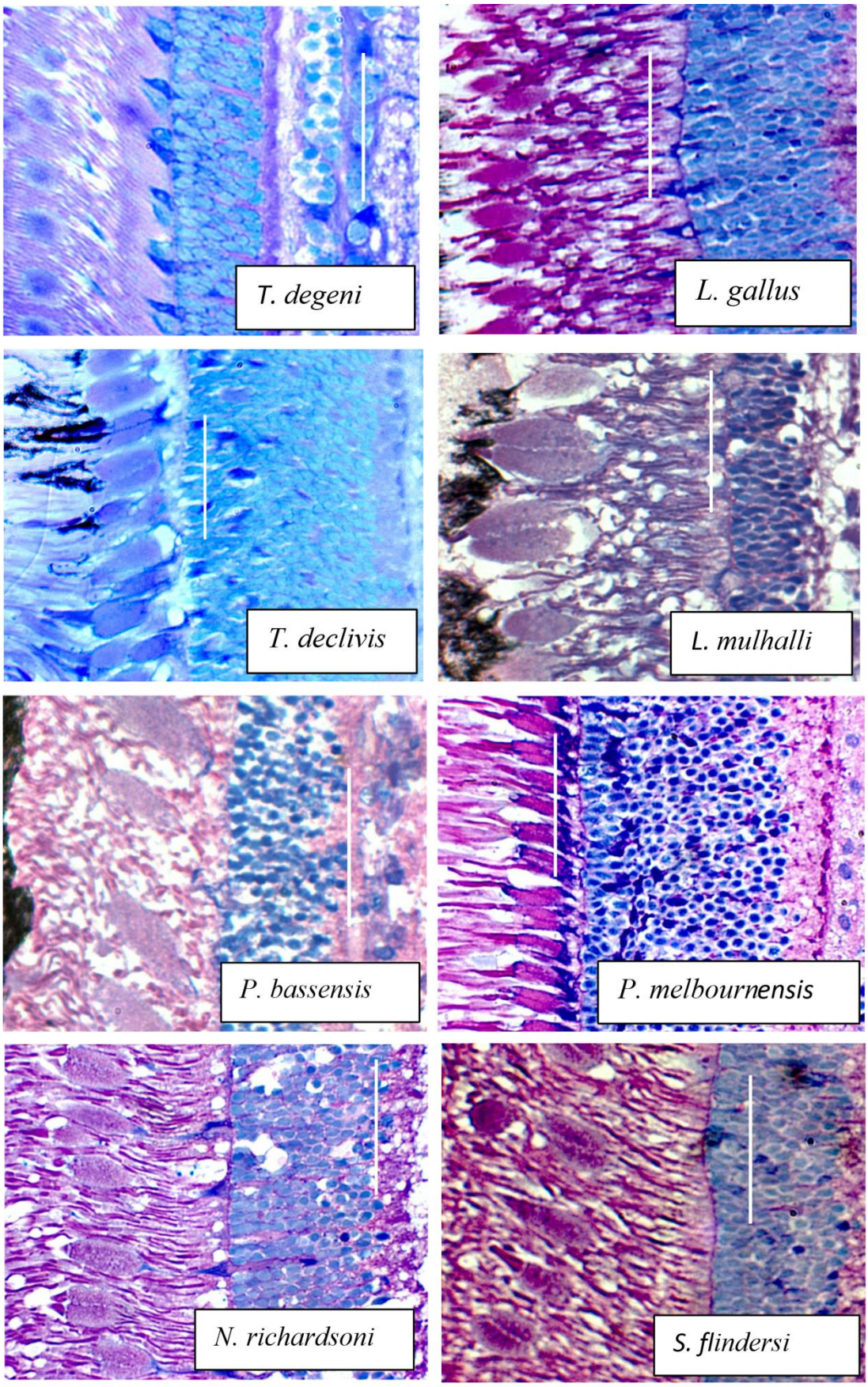

Figure 4: Transverse section of eight different fish species studied from benthic trawls in North-Eastern Tasmania. The scale bars are all 40 µm.

A logarithmic function described the relation between double cone size (measured as cone diameter), and cone density (Figure 5). 72% of the decrease in double cone size was predicted to be a function of cone density. The double cone was not able to be measured for *P. richardsoni* and was excluded from these results.

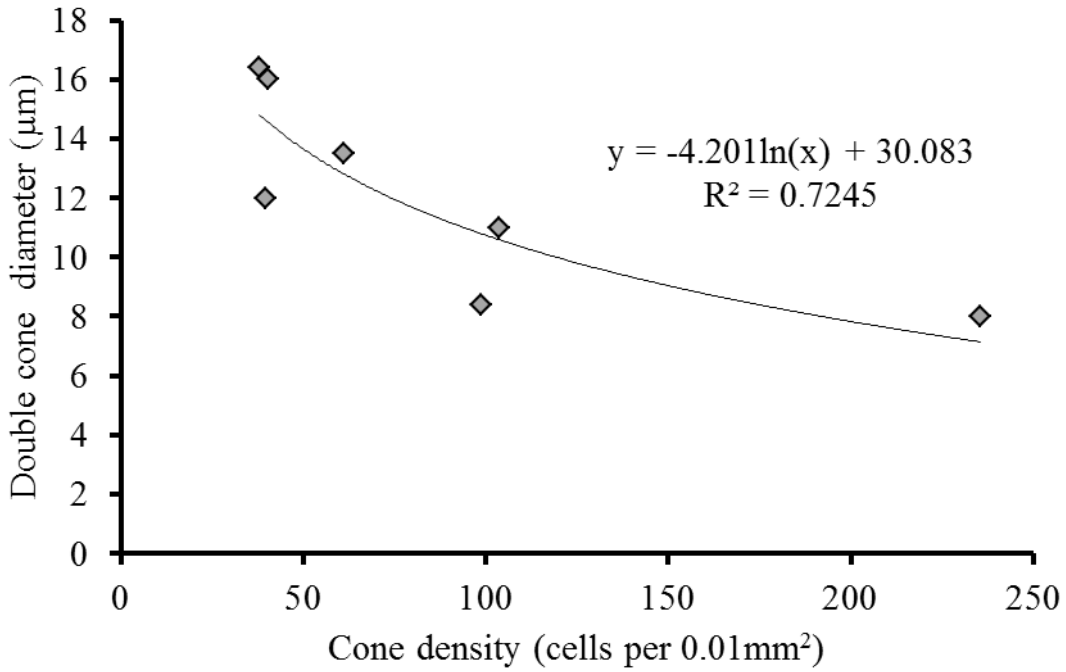

Figure 5: Relationship between mean diameter (µm) of double cones and the cone density for seven of the species studied from benthic trawls in North-Eastern Tasmania, with logarithmic equation.

The mean density of cones (cells per 0.01 mm^2) was significantly different between species (ANOVA, $F_{7,72}$= 32.564, P<0.001). Post-hoc analysis showed that species were in three main groups (Figure 6). *Sillago flindersi*, *N. richardsoni*, *P. bassensis*, *L. mulhalli* and *T. declivis* all had 38-60 cones per 0.01 mm^2. *Thamnaconus degeni* and *L. gallus* had almost double this density, with ~100 cones per 0.01 mm^2. *Parequula melbournensis* had over four times the density of the first group with 235 ± 29 cones per 0.01 mm^2.

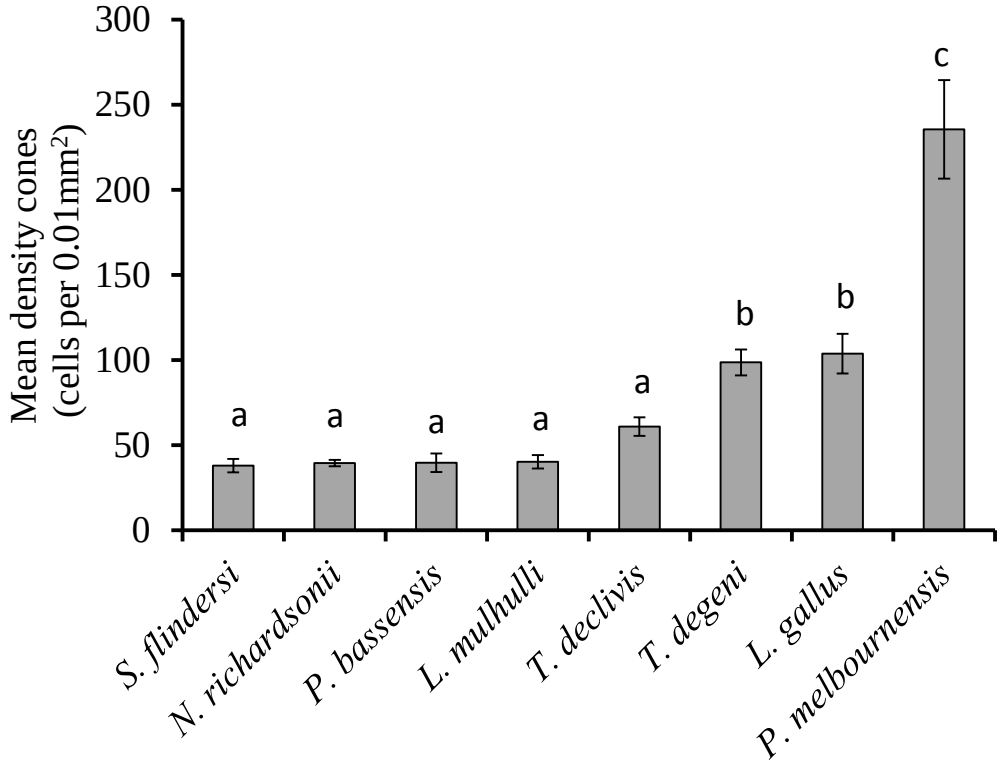

Figure 6: Mean density of cones (cells per 0.01 mm^2) ± SE, in eight different teleost species studied from benthic trawls in North-Eastern Tasmania. Common letters represent values that are not significantly different.

4.3.4. Cone Mosaics

Double cones were present in the mosaics of all species. With the exception of *T. declivis*, the double cones were arranged as a set of four around a single cone (Figure 7). This arrangement varied slightly for each species with respect to the size of the cone cells. *Trachurus declivis* had only rows of double cones.

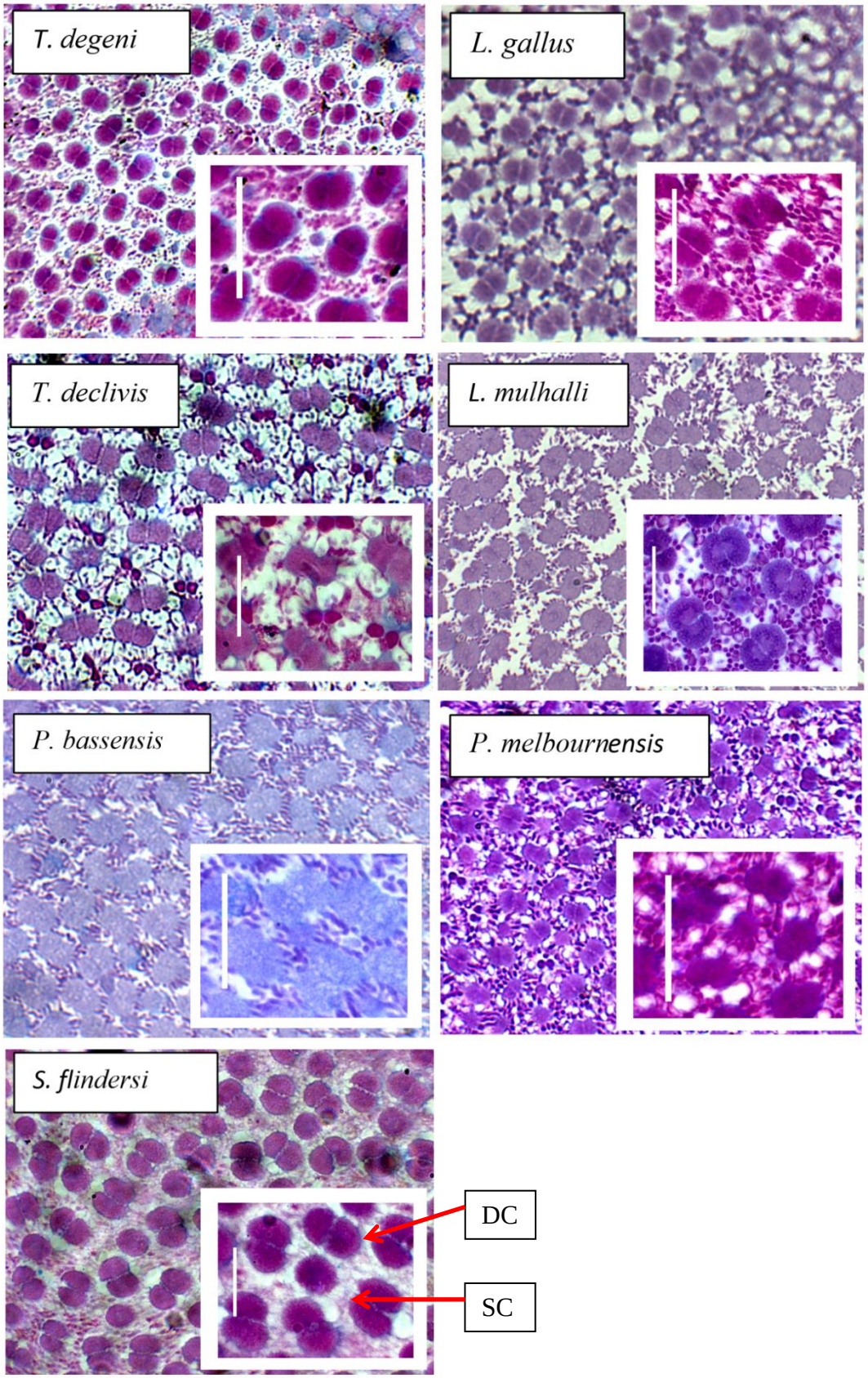

Figure 7: Tangential sections revealing the cone mosaic patterns in seven different fish species studied from benthic trawls in North-Eastern Tasmania. Each micrograph is 400 x magnification while inset is 1000 x magnification.The scale bars (shown for insets only) are all 40 µm. DC= double cone; SC= single cone.

4.3.5. Minimum separable angle and potential visual acuity

Mean MSA and VA were significantly different between the eight species studied (ANOVA, $F_{7,32}$= 28.93, P<0.001, and $F_{7,32}$=15.15, P<0.001, respectively) (Figure 8, Table 4a). *Lophonectes gallus* had the lowest value of VA, 0.078, while *L. mulhalli*, *S. flindersi*, *T. degeni*, *T. declivis*, *N. richardsoni* and *P. bassensis* had from 0.125 to 0.171. *Parequula melbournensis* had the highest value of 0.310. Retinal magnification (RM) was also significantly different between the eight species (ANOVA, $F_{7,32}$= 65.37, P<0.001), Table 4b).

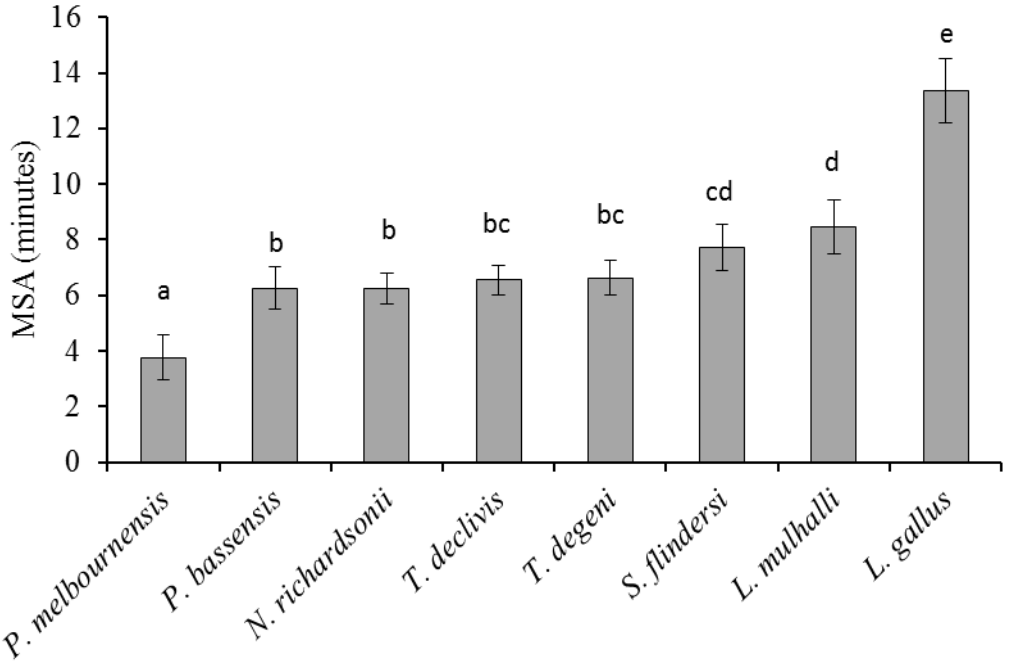

Figure 8: Mean MSA ± SE, in eight different temperate fish species studied from benthic trawls in North-Eastern Tasmania. Common letters represent values that are not significantly different.

Table 4a: Potential visual acuity (VA) in eight different temperate fish species indicating the subsets from post-hoc analyses. Common letters represent values that are not significantly different. Note: species are listed in order of highest to lowest VA for ease of interpreting subsets.

Species	Subset	VA
P. melbournensis	a	0.3104
P. bassensis	b	0.1713
N. richardsonii	b	0.1658
T. declivis	b	0.1573
T. degeni	b	0.1576
S. flindersi	b	0.1359
L. mulhalli	bc	0.1248
L. gallus	c	0.0774

Table 4b: Retinal magnification (RM; degrees) in eight different temperate fish species indicating the subsets from post-hoc analyses. Common letters represent values that are not significantly different. Note: species are listed in order of highest to lowest RM for ease of interpreting subsets.

Species	Subset	Retinal magnification (°)
L. gallus	a	20.61
T. degeni	b	10.40
L. mulhalli	c	8.49
P. melbournensis	c	8.26
T. declivis	c	8.15
S. flindersi	cd	7.31
N. richardsonii	d	6.32
P. bassensis	d	5.93

4.4. Discussion

4.4.1 Dimensions of the eye

An increase in both eye diameter and lens diameter occurred with an increase in total fish length in five of the species assessed based on a linear relationship. This increase was in agreement with other studies (Fishelson *et al.* 2004; Hajar *et al.* 2008; Miyazaki *et al.* 2000). For those species that did not show a strong correlation in this study, this was likely due to the limited range of lengths of the specimens collected. In contrast, the correlation does not apply to deeper water species, where it is hypothesised that there is a limit on the space in the retina for accommodating photoreceptor cells, and in this environment larger eyes are observed relative to fish size (Kirschfeld 1976). There were no deep water species encountered during the trawls in this study. This study also found that with increasing cone densities there was a decrease in the diameter of each double cone which agrees with the findings of Boehlert (1978). It is also recognised that, relative to fish size, eye size is generally larger in carnivores than herbivores (Pankhurst 1989). This was not the case in this study as it was found that the two species with the largest eyes, *P. bassensis* and *N. richardsonii*, had the smallest eye diameter to total length ratios. These two carnivorous flathead species had the smallest ratios, followed by *T. degeni* which was the only herbivore of the eight species. The largest eye sizes in relation to fish length were *L. muhulli* and *P. melbournensis*.

4.4.2 Rods

Trachurus declivis had only 7.6×10^6 rod cells per mm^2 of retina, which was different to the previously reported value of 1×10^7 rods per mm^2 in a closely related species, yellowtail horse mackerel (*Trachurus novaezealandiae*), from shallow waters of North-Eastern New Zealand (Pankhurst 1989). Normally, the slight difference seen between the *Trachurus* species could be attributed to the species inhabiting different ranges of depths (Edgar 2008), however in this case the maximum depth of both species is 500m (Gomon *et al.* 2008). Alternatively, it could be due to environmental conditions during larval development (Fishelson *et al.* 2012; Shand 1997). *Trachurus declivis* are more commonly found in deeper waters and the juveniles are more likely to be found offshore than *T. novaezealandiae*. As such, it would be expected that *T. declivis* have greater rod density but this is not the case here. Thus, the difference seen could be due to natural interspecies variation. This could be tested by estimating the rod densities of other *Trachurus* species for further comparison. No

other studies on photoreceptor cell densities exist for *L. mulhalli, S. flindersi, N. richardsoni, P. melbournensis, P.bassensis, L. gallus and T degeni* or other closely related species.

A high density of rods is normally attributed to deeper habitat ranges (Eastman 1988; Mas-Riera 1991). In this case, *T. declivis* is known to inhabit a maximum range of 500 m (Gomon *et al.* 2008), which is much deeper than the seven other species examined in this paper, all with lower rod densities. It is evident that the mean number of rods per mm^2 increases with the expected maximum habitat depth of the species (Figure 9). While *T. declivis* had the greatest number of rods, *N. richardsoni*, *S. flindersi* and *L. gallus* had the highest rod densities relative to the other estimates. The maximum habitat range of *N. richardsoni, S. flindersi* and *L. gallus* extends to 160-240 m depth (Gomon *et al.* 2008).

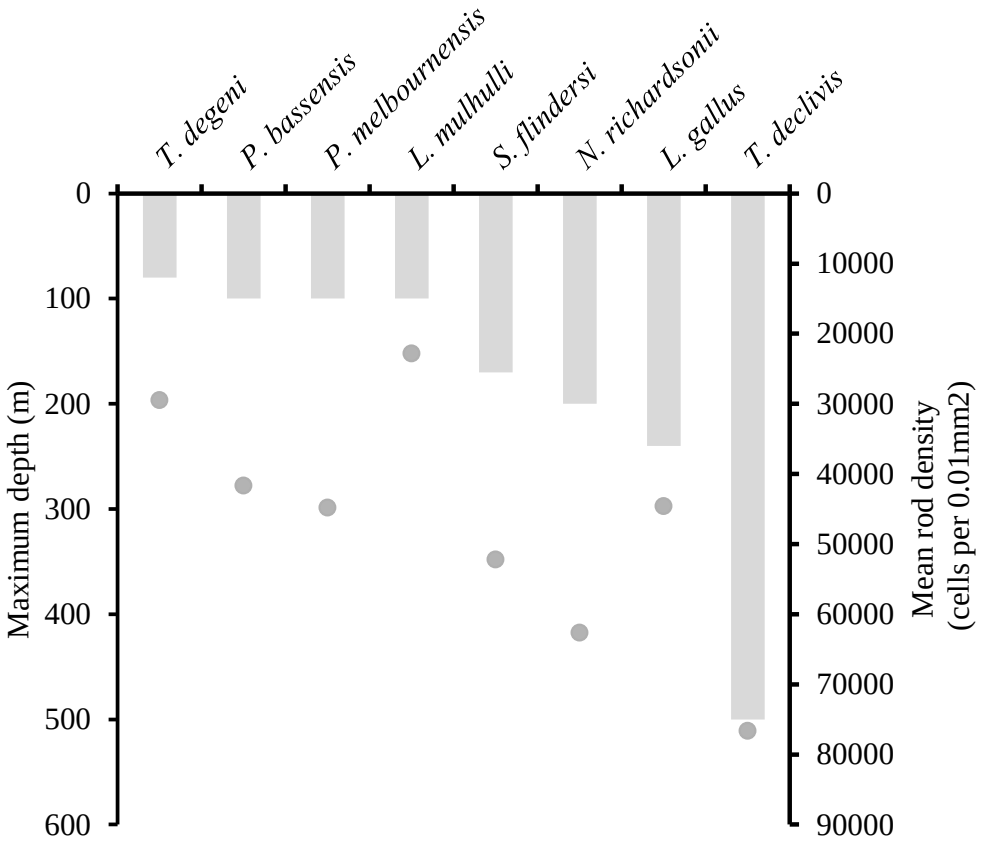

Figure 9: Maximum habitat depth profile (m) (bars) of eight bycatch species with mean rod density (cells per $0.01mm^2$) (dots). Depth data from Edgar (2012).

On the other end of the scale, *P. melbournensis, T. degeni*, and *P. bassensis* all had the lowest rod densities and inhabit waters up to 80-100 m deep. Even in closely related species this was the case, for example, *N. richardsoni* have more rods than *P. bassensis* probably because the former are found up to 60 m deeper. This is because rods are adapted for detecting dim light, and therefore are more valuable for fish to perceive visual cues in low light intensity conditions associated with deep water (Fernald 1988). For *T. declivis*, having the highest density of rods would make this species to be more likely to respond quickly to lights, since rods are sensitive to the shift from dark to light (Bond 1996). The only species that did not follow this trend was *L. mulhalli*. This species is usually located at depths up to 100 m but had the lowest estimate of rod density. However, of the eight species, this species has the largest eye diameter to total length ratio. This could be an adaption that allows for a larger depth range of the species. Alternatively, it could simply be a reflection of the time actually spent at its maximum range.

4.4.3 Cones

The densities of cones were found to be less variable among species in this study than rod densities. While foveae (specialised regions of high cone density) do occur in some fish species (Douglas and Hawryshyn 1990; Wagner 1990), this feature was not assessed in this study and average cone densities in dorsal and ventral regions were used for ease of species comparisons. *Parequula melbournensis* had the greatest density of cones which suggests that they are adapted to shallow habitats, but they are found in depths of greater than 100 m (Fishelson *et al.* 2012). This species is apparently diurnal (mostly active during the day), as are most of the other species in this study (Edgar 2008), suggesting they would be less reliant on rods. The high cone density of *P. melbournensis* could be due to the fact that this is a schooling species (Edgar 2008), requiring visual cues to maintain orientation in a group. However, *T. declivis* also exhibits schooling (Gomon *et al.* 2008), and had a much lower cone density. While it has been shown that certain species have vision dependent schooling behaviours (Kowalko *et al.* 2013), most fish use the lateral line as the dominant mechanism for schooling (Larsson 2012).

Conversely, *S. flindersi, N. richardsoni, P. bassensis, L. mulhalli* and *T. declivis*, all had the lowest density of cones. It could be assumed that in the relatively shallow depth that light can penetrate (to ~100 m), the absolute densities of cones are not as important as the types of cones available. It has been demonstrated that single cones and double cones (and perhaps

also triple cones, that were not observed in this study) are sensitive to different wavelengths of light (Loew and Lythgoe 1978; Marc and Sperling 1976; Tamura 1957; Ullmann *et al.* 2011). Consequently, cones are used for both high intensity light detection and to perceive different colours (Losey *et al.* 1999). By using microspectrophotometry, the presence of UV cones in the retina can be detected. There are four main pigments that can be found in the retina of teleosts including double cones with red and green pigments, long single cones with blue pigment and short single cones with UV-sensitive pigments (Bowmaker 1990; Raymond *et al.* 1995). The visual pigments of fishes are 'offset' to create contrast and therefore increase the visibility of objects and other fish underwater (Lythgoe 1968). In general, pelagic fish only require the contrast of prey when coming up from deeper water or looking down on the prey from the surface (McFarland and Munz 1975). Coral reef fishes on the other hand appear to be more complex and their downward visual fields differ dramatically due to the spectrum of colours that are involved (McFarland and Munz 1975).

Not only are the the eyes of certain species adapted for specific light intensities and light spectra, but their spectral sensitivity may also correspond to plankton colours, and dissolved and particulate materials (McFarland and Munz 1975). Different wavelengths may be used for foraging [prey/food detection] and prey selection [prey choice] (Cheney *et al.* 2013). Triggerfish have demonstrated a preference for the colour red which may stem from the need for carotenoids (Cheney *et al.* 2013). Other species have also shown a preferential foraging for the colour red as it appears to be the main colour of their diet that includes invertebrates and corals (Cheney *et al.* 2013). Spectral sensitivity (or 'wavelength sensitivity') may also play an important role in vision during spawning, where UV wavelengths can play a role in the choice of a mate (or 'in mate selection') (Rick and Bakker 2008; Rick *et al.* 2006; Smith *et al.* 2002). The use of colour vision may also influence the aggressive male-male interaction within species (Braun *et al.* 2014; Lehtonen 2014).

4.4.4 Cone mosaics

Studies of the cones mosaics of teleost species date back to as early as 1900 but the importance of these mosaics is still a mystery (Boehlert 1978; Eigenmann and Shafer 1900). More recent studies are starting to reveal the benefits of complex arrangements of cones to the species that most rely on vision. The cone mosaic for six of the eight species in this study had a similar arrangement of four double cones around a center single cone, which is a common arrangement, especially in shallow water species (Boehlert 1978; Mas-Riera 1991;

Wagner 1990). *Trachurus declivis* was different, with rows of double cones, which is a known pattern for species in deeper water habitats and shoaling species (Boehlert 1978). This is contrary to a similar species, *Trachurus mediterraneus ponticus*, which has a regular structural organization of four double cones around a single cone (Podugolnikova 1985). This difference is unexpected since both species are deeper water shoaling species. There are no studies in species similar to *L. mulhulli, S. flindersi, P. melbournensis, P.bassensis, L. gallus and T degeni.*

An organisation that has been identified as similar to that of the regular structural organisation has additional single cones in the corners of the 'square' (Boehlert 1978). This type of regular structural organisation of cones in a mosaic often occurs in juvenile fish and changes with the growth of the fish (Boehlert 1978). The arrangement of the cones into a mosaic may reflect the neural circuitry of the retina (Evans and Browman 2004). Cones are apparently arranged in a particular pattern to match that of the bipolar cells (Podugolnikova 1985) which in turn are responsible for transporting information from the photoreceptor cells to the ganglion cells and then through the optic nerve to the brain (Wagner 1990).

Since the ability of fish to define detail is determined by the focal length, the retinal magnification, and the number of cones covered by the projected image, the cone mosaic does not seem to reflect the potential visual acuity of a species. However, mosaics can be considered as more or less complex based on the arrangement of the different types of cells that confer colour sensitivity (Boehlert 1978; Losey *et al.* 1999). As such, the shallow water species in this study would have increased visual capacity with a cone mosaic that can allow for detection of different light spectra.

4.4.5 Minimum separable angle and potential visual acuity

Potential visual acuity is a fish's ability to detect fine detail in an object. This can be expressed as minimum separable angle (in minutes of arc) or potential visual acuity (VA). The minimum separable angle (or MSA) is a theoretical estimate of acuity and is defined as the minimum angle at the eye for distinguishing between two separate objects (Douglas and Hawryshyn 1990a). The potential visual acuity is the inverse of the MSA and is defined as the minimum angle which light can subtend at the eye and still be resolved (Neave 1984). Estimates such as these are important for understanding the visual capabilities of fish, for example, the distance from which a fish can detect an object such as prey.

The MSA for *T. degeni* (6.6 minutes) was very similar to that of another Monocanthidae species, *Cantherines modestus* which had a value of 6.4 minutes (Tamura 1957). However, the MSA of *L. mulhalli* (8.5 minutes) was higher than a related species *Chelidonichthys kumu* (6.8 minutes) (Tamura 1957). This difference was most likely due to the larger size of the specimens examined, for example *C. kumu* grows to around 500 mm (Gomon *et al.* 2008) while the mean size of the *L. mulhulli* in this study was 172 mm. An increase in eye size has a substantial effect on increasing resolution, and occurs during fish growth (Mas-Riera 1991; Neave 1984; Shand 1997). This improved resolving power is due to the tissue of the eye expanding continuously through the life of an individual fish. Although the cone density actually decreases, more cones and more surface area is exposed to the light from an image, increasing the resolving power of the eye (Powers and Raymond 1990).

S. flindersi and *T. declivis* from this study were not similar to their Japanese counterparts of the same size; the MSA for *S. flindersi* (7.7 minutes) was less than that of the *Sillago japonica* (10.0 minutes), while in *T. declivis* (6.6 minutes) MSA was less than *Trachurus japonicus* (7.7 minutes) (Hajar *et al.* 2008). The two *Sillago* species have many similar characteristics such as habitat and maximum length, however the difference in depth range (up to 170 m for *S. flindersi* and up to 30 m for *S. japonicus*) may be the key factor to the differences in these values (Matsuura 1985). Similarly, the maximum habitat depth of *T. declivis* (up to 500 m) is deeper than the maximum depth for *T. japonicus* (275 m) (Matsuura 1985). The Japanese species have higher MSA (lower resolution) even though they occur in shallower water with higher light intensity.

Potential visual acuity is dependent upon cone cell density in the calculation, and therefore these results tended to reflect similar patterns among the eight species. For this reason, *P. melbournensis* had the largest calculated potential visual acuity. However, lens size is also an important factor to determine potential visual acuity, which contributed to *L. gallus* possessing the lowest potential visual acuity of the eight species. The other six species (*P. bassensis*, *N. richardsoni*, *T. declivis*, *T. degeni*, *S. flindersi* and *L. mulhalli*) were not significantly different. Having higher potential visual acuity is beneficial to an individual as it allows them to better distinguish fine detail at a greater distance. The benefits could range from finding food, to avoiding predation, or avoidance of commercial fishing gear (Hajar *et al.* 2008; Walsh and Hickey 1993; Zhang and Arimoto 1993). After receiving the visual information, however, it must be translated by the neural processing center and this is what dictates a reaction by fish (Anderson 1988). Importantly, visual ability alone is not the only

contributor to fish behaviour and other sensory input (mechanosensory and chemosensory) may be critical especially for crepuscular or deep water species (Douglas and Djamgoz 1990). Retinal convergence and higher order neural processing of visual information will also impact available visual stimuli, and detection of a visual cue alone cannot determine a fish's response to escape, swim towards or not respond to the stimulus. This research did not investigate higher order neural cells (e.g. biplolar, amacrine, ganglion) but focused on the potential for detection of light and colour signals in the retina through assessment of eye morphology and photoreceptor densities and arrangement.

Relating the structure of the eye to its function allows for further understanding of a particular species' life history, reproduction, feeding mode, and interactions with other individuals. It can also allow us to interpret a fish's reaction or response to human activities whether it is aquaculture, dams in a river, oil rigs or wave energy converters in the ocean, and even commercial fisheries practices. In particular, the reaction of fish to trawling has been studied extensively for a variety of species (Glass and Wardle 1989; Haugland and Misund 2011; Piasente *et al.* 2004). With the use of cameras attached to trawl nets we are able to see the differences between species as they are encountered by the mouth of a trawl (Hajar *et al.* 2008; Zhang and Arimoto 1993). It has also been observed that fish are able to elicit an ordered response in front of a trawl when encountered during the day (or when illuminated) versus in the dark (Walsh and Hickey 1993), which gives more credence to the importance of vision. This chapter provides the information required to predict the catch rates of a certain species as we can compare the relative potential visual acuity and therefore estimate which fish will be better equipped to visually detect and respond to an approaching trawl. Based on retinal morphology and calculated potential visual acuity, *T. declivis* (high rod density) and *P. melbournensis* (high cone density, high potential visual acuity, and large relative eye size) were the species in this study most likely to react to lights used on fishing gear. The next step is to examine the swimming ability of each of these species. This will allow for the validation of this kind of prediction and provide quantitative evidence of the vulnerability of these bycatch species to commercial trawling operations.

4.4.6. Conclusion

Across the eight key species studied, it was found that *P. melbournensis* had the highest visual acuity, while *L. gallus* had the lowest. It was seen that species that inhabited deeper maximum depths had greater number of rods. It was also found that these deeper water

species have different cone mosaic patterns to those found in shallow waters. By estimating the potential visual acuity of different bycatch species, calculating rod density, and reviewing the implications of specific photoreceptor mosaic patterns, the potential vulnerability of the species to the fishing gear could be suggested. Importantly, additional characteristics of fish are likely to impact on escape response, for example other sensory input (Bond 1996; Pankhurst, 1989), retinal convergence, and higher order neural processing (Douglas & Hawryshyn, 1990). However, for temperate shallow water species, including those in this study, the dominant sensory modality is vision (Douglas and Hawryshyn 1990a; Pankhurst 1989). In terms of the commercial fishery, in particular trawling, where a mix of fish are caught but only a select few species are kept, these data can inform mitigation techniques such as the use of light to reduce fish bycatch. The use of light could aid in increasing the sensory detection of fishing gear, resulting in a visual cue for fish to detect an oncoming trawl and potentially elicit an escape response.

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CHAPTER 5: Maximum swimming speeds of eight finfish bycatch species from North-Eastern Tasmania

5.1. Introduction

The speed at which a fish can swim is determined by a combination of the movement of the muscle structure, shape of the fish and the fins (Webb 1984). The way the fish moves relates to the habitat and activities of the species and is reflected in the shape of the fish (Fulton *et al.* 2005; Sambilay 1990; Webb 1984). Years of evolution have allowed each species to adapt for its lifestyle requirements, whether it is chasing prey or migrating through oceans.

Swimming can be categorised by the use of particular fins, such as caudal fin, pectoral fins and dorsal/anal fin swimmers. For predominantly caudal fin swimmers there are five swimming modes: anguilliform; subcarangiform; carangiform; thunniform; and ostraciiform (Lindsey 1978). Swimming modes allow us to group certain species together based on the shape and movement of fish and are classified by the amount of undulation in the body during swimming, the fins predominantly used for swimming, and the size and shape of those fins. These modes have a strong correlation to body morphometrics. There have been attempts to correlate the morphometrics of fish with its mode of swimming and the swimming speed (Videler 1993). For example, Sambilay (1990) developed models to predict the absolute and relative swimming speeds of a fish given its length and shape.

There are three different types of swimming speeds identified in fish; sustained swimming, prolonged swimming, and burst swimming (Beamish 1978). Sustained swimming is used by migrating and schooling species and is maintained for longer than 200 mins (Hammer 1995). Prolonged swimming includes speeds that can be maintained for between 20-200 mins. In contrast, burst swimming speeds occur for only a few seconds but are essential for species to capture prey and avoid predators (Beamish 1978). It is generally recognised that burst speeds are the most difficult to accurately estimate both in the laboratory and at sea (He 1993). As such, indirect methods have been used instead. Since the burst speed is not measured directly, this estimate is referred to as the maximum swimming speed. The maximum swimming speed can be estimated from the contraction time of the muscle and an estimation of the stride length of the fish (Arimoto *et al.* 1991; Riyanto *et al.* 2014; Wardle *et al.* 1989; Wardle 1977). Muscle contraction controls the movement of the tail from side to side during propulsion while stride length is the distance swum in one full cycle of the tail of a fish (Videler and Wardle 1991).

Since it is difficult to accurately measure burst speed or estimate maximum swimming speed it would be beneficial to find a relationship between the known maximum swimming speed of a fish and a measureable external trait. The aspect ratio is a formula based on measurements of a fin, most commonly the caudal fin. It describes the height of the fin to the surface area and gives an indication of the shape of the fin. Species with higher caudal fin aspect ratio indicate faster and more powerful swimmers. Examples include the large pelagic piscivores, tuna (*Thunnini* spp) and marlin (*Istiophoridae* spp) (Block *et al.* 1992; Gero 1952a). These species have narrow and high caudal fins. On the other end of the spectrum are eels, fish larvae and fish that display snake-like movements that have very small or absent tails (Lindsey 1978).

In the last two chapters, the experiments testing the effect of light, as well as examining the visual capabilities of the eight fish species of interest from North-Eastern Tasmanian waters have been conducted. The final factor to be considered is the swimming capacity. This chapter investigates the maximum swimming speeds of the eight fish species of interest from North-Eastern Tasmanian waters for the purposes of investigating their response to underwater lights attached to the headline of a trawl. Studies of swimming speeds are usually conducted on commercial species (i.e. tuna and salmon) and only a few have considered bycatch species (Fulton *et al.* 2005; Plaut 2001; Walker *et al.* 2013) and in particular their interactions with commercial fishing gear. The aim of this study, therefore, is to measure and estimate the maximum speeds of these species. This study will also attempt to use historical data to find a correlation between morphometrics and estimated maximum swimming speeds as a way of predicting the maximum swimming speed.

5.2. Methodology

5.2.1. Calculation of maximum swimming speed

Fish were collected during November 2014, using a single Florida Flyer prawn trawl net onboard the Australian Maritime College fisheries training vessel, the *FTV Bluefin*. The trawl net has a 14 meter headline and a codend stretched mesh size of 40 mm with 100 meshes in circumference. All trawling was done during the night at water depths ranged between 35 and 40 meter with 45 minute tow duration. The water temperature ranged between 15.3 and 15.8 degrees Celcius. The trawling grounds were located the North-Eastern coast of Tasmania

between the coordinates of 41°00"818' South, 148°22"074' East and 41.03"498' South, 148.19"945' East.

As per the previous chapter, there are eight species of interest, however, due to the high mortality of some species that are caught with the trawl, only five species were studied. A total of 29 individuals from the five species were sampled including sand flathead (*Platycephalus bassinsis*), jack mackerel (*Trachurus declivis*), Degen's leatherjacket (*Thamnaconus degeni*), silver biddy (*Parequula melbournensis*), and roundsnout gurnard (*Lepidotrigla mulhalli*). Captured fish were placed in a 1500 L tank on board as quickly as possible after the trawl net was brought on deck and the codend was emptied. To increase survivability the fish were carefully removed from the net and transported in a bucket of water. They were left to recover from capture for at least 48 h before swimming speed experiments were conducted. This time frame allows for the fish to become rested and for their cortisol levels to return to normal (Milligan and Wood 1986; Wardle 1980).

While sampling, many of the species had a high post-capture mortality rate and it was difficult to keep individuals alive. This resulted in a low sample size for these species and meant that some individual fish were not in an ideal condition for the experiment. However, for the purposes of demonstrating the commonly-used technique to measure the swimming speed of bycatch species while at sea, all results are provided, including those individuals that may have been affected by the sampling process.

5.2.1.1. Stride length

In order to assess swimming speed, individual fish were transferred to a 120 L raceway tank (35 x 80 x 45 cm), which was also set up on the research vessel deck (Figure 1). The base of the tank was marked with a 5 cm grid as a reference for determining stride length. The raceway had fresh sea water flowing into the tank using the deck hose in order to maintain the quality of the water during the trials. The hose was removed prior to the start of each individual test. As such, during the experiment the water flow was considered to be zero. The fish were left to acclimate for 10 minutes before each test. Each individual was 'stimulated' by tapping the tank so that the fish swam at their maximum speed within the experimental tank system following the methods of Yanase *et al.* (2007). The movement of each fish was recorded by a video camera (Go-Pro Hero 3, USA) positioned 0.5 m above the raceway on a polypipe frame with 127° field of view. The fish was encouraged to swim the entire length of the tank. This method was used instead of direct speed measurements due to

the stress to the fish imposed by being captured in a trawl net, post-capture handling and holding prior to filming, and their effect on the maximum swimming speed of the fish.

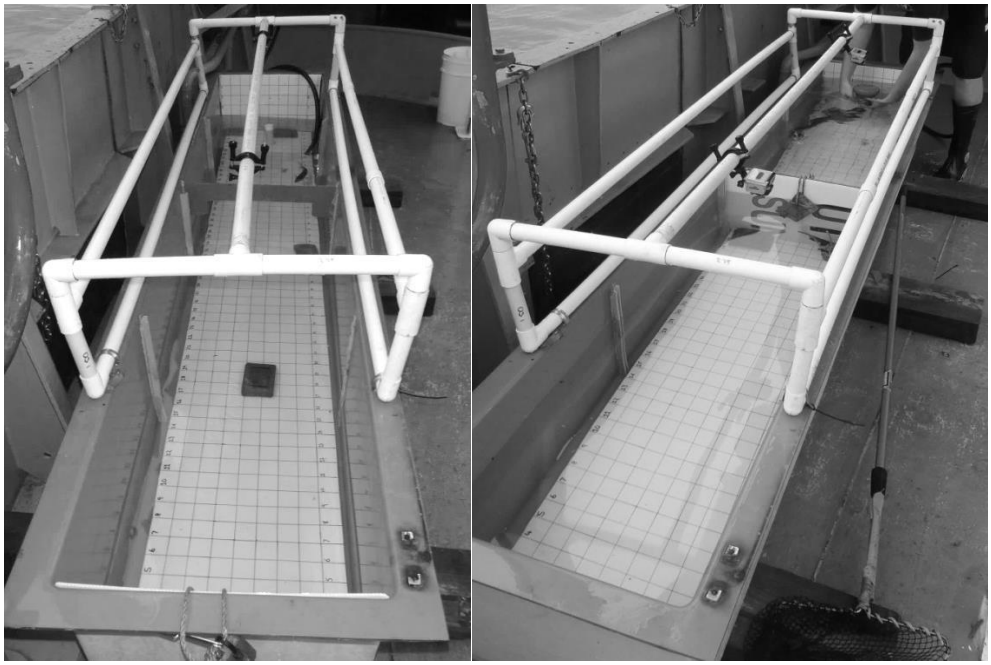


Figure 1: The experimental raceway in position, on board *FTV Bluefin*, used to measure maximum speed of finfish bycatch species from North-Eastern Tasmania. A Go-pro camera is attached to the white PVC pipe frame and used to film the dorsal view of the fish in the tank (photograph: Darcie E Hunt).

Using the Go-Pro footage of each individual swimming in the raceway (described above), the stride length was determined from the distance swum during one oscillation of the tail using the method of Arimoto *et al.* (1991). The movement of the tail from one side of the body to the other and back represents one full oscillation of the tail. The footage was slowed to 0.125x using Window Live Movie Maker (2010 Microsoft Corporation). Using the 5 cm grid on the bottom of the raceway the distance was calculated with trigonometry to find the distance the fish travelled as the nose of the fish passed each line. The stride length was measured during its maximum speed in the tank, and was reported relative to total body length. Within one piece of video footage, three replicate stride lengths were calculated for each replicate fish. Between replicates the fish were allowed to rest for 5 mins. No measurements are taken during the initial stride when swimming from a stationary position, due to lack of momentum (Videler and Wardle 1991).

5.2.1.2. Muscle contraction

After the swimming assessment, fish were removed from the raceway and euthanised immediately with a spike to the head (aka the *ikijime* or spiking[1] method). Each individual fish was measured using a measuring board for total length (to the nearest mm) and photographed for later analysis to determine caudal fin aspect ratio (see Section 3). The fish were then dissected within 5 minutes post mortem. For consistency in sampling a muscle block was taken from the same place in all species. The muscle block was removed from the left side of each fish, behind the pectoral fin (Figure 2). The needles were placed perpendicular to the muscle blocks. The height of the muscle block was the same as the depth of the fish and the width was approximately 1/5 of the length of the tail.

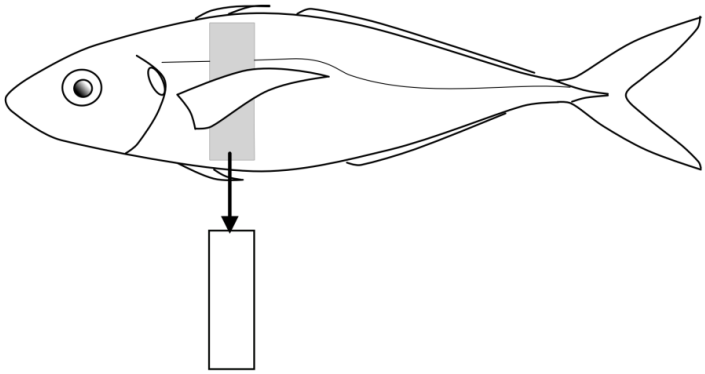


Figure 2: Diagram of *T. declivis* showing the position of the muscle block removed from the left side of the fish, directly behind the pectoral fin.

Two needle electrodes were inserted into the dissected muscle block and attached to a specially made isotonic muscle transducer following the methods of Riyanto *et al.* (2014) and Yanase *et al.* (2007). An electric stimulus pulse (15 Volts for 2 milliseconds) was applied to induce the muscle block to contract using an electric pulse generator (Gould advanced Pulse Generator PG 58A). The muscle transducer converted the muscle contraction into a voltage that was amplified by a strain gauge amplifier (Measurements Group, North Carolina). The stimulus pulse and the muscle contraction were displayed on a portable oscilloscope (Fluke 190-062 Scopemeter) (Figure 3 and Figure 4). Twitch contraction time was measured from the time of the stimulus to the maximum contraction of the muscle (the peak in the curve,

[1] Inserting a spike into the head to destroy the brain (Poli et al. 2005).

Figure 4). For each section of muscle, the stimulus was applied three times with 30 seconds in between and the smallest value was used for minimum muscle contraction time (s) following the methods of Yanase *et al.* (2007). Due to the fast, deterioration of the muscle, the first recording was usually the fastest contraction.

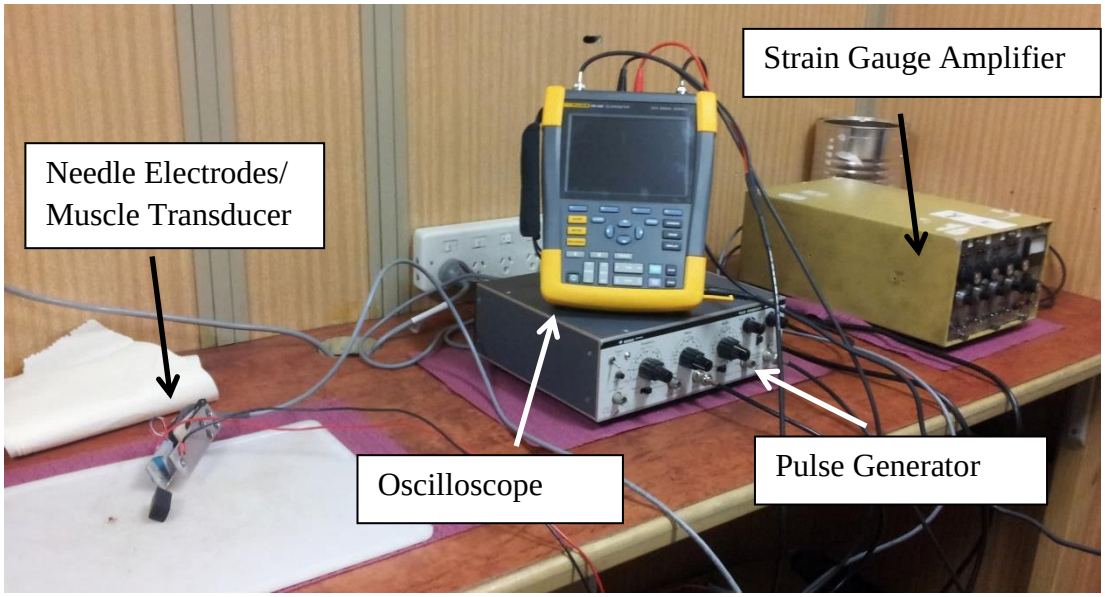


Figure 3: Set up of the experimental design for muscle contraction estimation in five finfish species from North-Eastern Tasmania (photograph: Darcie E Hunt).

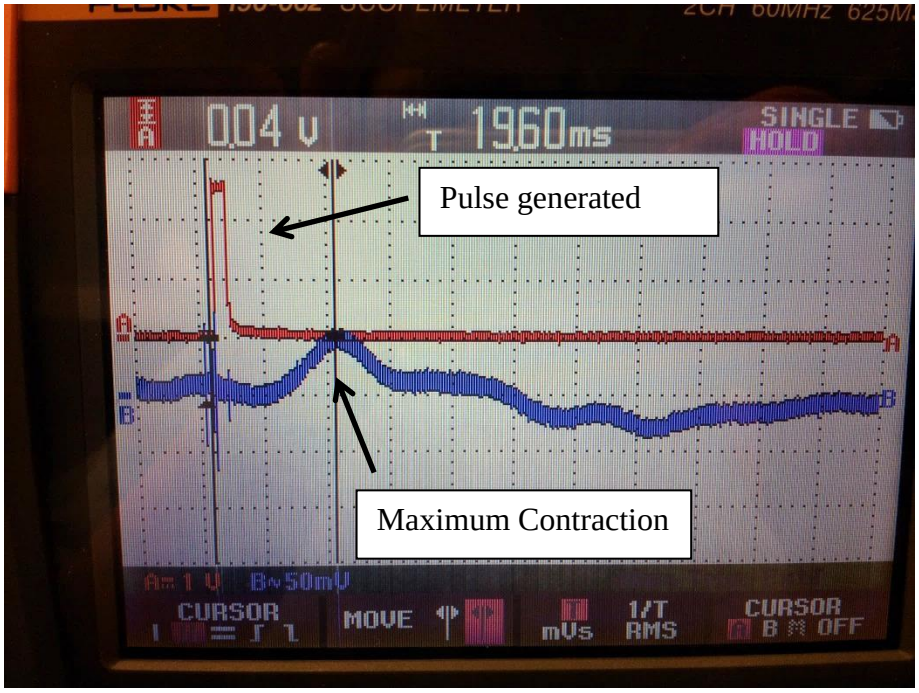


Figure 4: Example screen of oscilloscope displaying 5 V pulse generated (thin line) and contraction of the fish muscle (thick line), indicating time of pulse and the time of the maximum contraction (photograph: Darcie E Hunt).

5.2.1.3. Maximum swimming speed formula

Using the values for stride length in body lengths (BLs) and muscle contraction time (s), see above, the maximum swimming speed (m s^{-1}) was determined from the following equation (Arimoto *et al.* 1991):

$$Maximum\ speed = \frac{(TL\ x\ SL)}{2\ x\ T_{mc}}$$

Where *TL* is the total length of the fish (m), *SL* is the stride length of the fish (BLs), and T_{mc} is the minimum muscle contraction time (s). Error bar were presented as standard error of the mean calculated with the following.

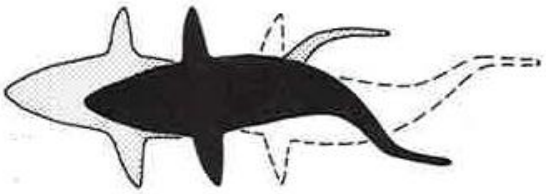
5.2.2. Estimates of swimming speed from historical data

In order to test a predictive approach, using a measurable external trait to estimate maximum swimming speed, the maximum (including 'burst') speeds of various teleost species were collected from a range of sources dating back to 1952 (see appendix for raw data). Only the studies that used methods to estimate maximum or burst speeds were used in this analysis. Prolonged, sustained and foraging speeds were not used. The fish studied in each swimming speed reference were categorised into swimming mode and caudal fin aspect ratio was determined.

5.2.2.1. Swimming modes of fishes

Each species was classified into a swimming mode. For the purposes of this study, only predominantly caudal fin swimmers were analysed. Only fish that were anguilliform, subcarangiform, carangiform, thunniform or ostracciform were considered and fish of any other modes (labriform, ballistiform etc) were removed from the analysis. Not all species in these swimming speed references were identified to a swim mode classification. For those that were not, the modes were found from Froese and Pauly (2014) or were added using the classification system derived from Lindsey (1978) (Table 1)**.**

Table 1: Classification of teleosts caudal fin swimmers, with swimming behaviour described and dorsal view diagrams of fish during typical movements. (Characteristics have been summarised from Lindsey (1978)).

Swim mode	Characteristics	Picture
Anguilliform	Undulation of whole body; body shape is long and thin; almost no caudal fin.	
Subcarangiform	Snout moves side to side; fewer undulations than anguilliform. Straight or rounded caudal fin.	
Carangiform	Only posterior 1/3 body flexes ; stiff caudal peduncle; scooped caudal fin.	
Thunniform	Only posterior 1/3 body flexes ; high stiff caudal fin; very narrow caudal peduncle.	
Ostraciiform	Body incapable of lateral flexing; caudal fin movement like pendulum.	

5.2.2.2. Caudal fin aspect ratio

For many of the swimming speed references the caudal fin aspect ratio was already provided. For those that were not the aspect ratio was provided by (Froese and Pauly 2014). The way in which these studies measured the caudal fin aspect ratio (AR) was using the formula:

$$AR = \frac{h^2}{s}$$

Whereby *AR* is the caudal fin aspect ratio; *h* is the height of the caudal fin; and *s* is the area of the caudal fin which is measured from the smallest part of the caudal peduncle to the tip of the fin. The way in which the measurements are made can be seen in Figure 5.

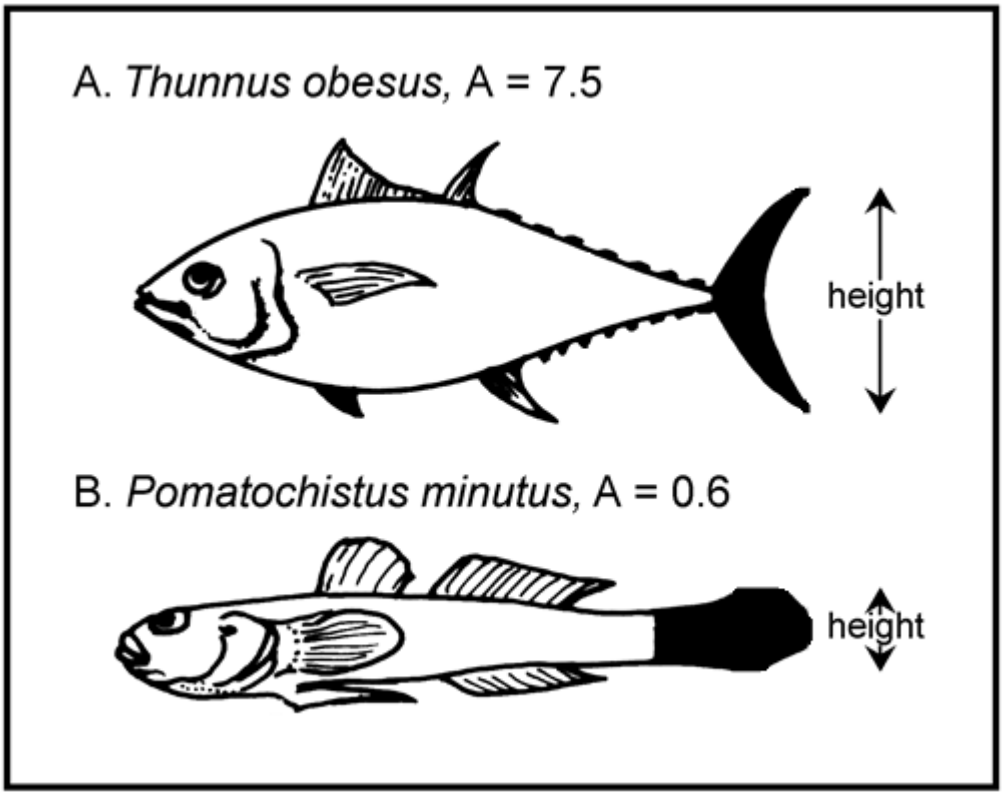


Figure 5: Diagrams indicating the measurements taken to calculate the caudal fin aspect ratio (AR) of finfish (modified from (Sambilay 1990). Caudal fin height (*h*) is represented by the arrows; area (*s*) represented by black shading.

5.2.2.3. Predictive formula

The maximum speeds (m s^{-1}) of these individuals were plotted against caudal fin aspect ratio (for many species speeds for more than one replicate fish were provided). Where speeds were reported in body lengths per second (BL/s), total length of the fish was used to convert the speed to meters per second (m s^{-1}). When the length of the fish was not provided, the data was not used. An exponential trendline was fitted to the data and the 95% confidence intervals were found using the least squares regression method in the statistical program R (version 2.15.3).

5.2.3. Validation of predictive formula

5.2.3.1. Swimming mode

Using the classification summarised from (Lindsey 1978), Table 1, the eight species of interest were classified into a predominantly caudal fin swimming mode. For those species that were recorded during sampling the video footage was used to classify the swimming mode. For species that were not sampled, online sources were used.

5.2.3.2. Caudal fin aspect ratio

During swimming speed trials in Section 1, fish were placed on a measuring board and digital photographs were taken of the caudal fin for later analysis. Care was taken not to over-extend the tail past its normal flexion. Species with high mortality, which were not assessed for swimming speed, were still photographed for the measurement of the caudal fin: tiger flathead (*Neoplatycephalus richardsonii*), crested flounder (*Lophonectes gallus*) and eastern school whiting (*Sillago flindersi*). Using the program *Image J* (Version 1.46r, National Institute of Health, USA), measurements were taken of the caudal fins including the area and height of the fin (as per Section 5.2.2.2.) to calculate caudal fin aspect ratio.

5.2.3.3. Observed versus Predicted speeds

In order to validate the use of the predictive formula (as per Section 5.2.2.3.), the maximum swimming speeds calculated for the five species of interest were plotted against the predicted curve. By using the ARs calculated, the speeds of these species were estimated with the predictive formula. The observed and predicted maximum swimming speed values for each of the five species were analysed with a correlation analysis.

5.3. Results

5.3.1. Calculation of maximum swimming speed

Seven out of the eight species of interest were encountered during sample collection. *Sillago flindersi* was not caught during trawling for the entire cruise. *Lophonectes gallus* individuals did not survive trawling and the one individual of *N. richardsoni* sampled did not survive the speed trials. As such, five of the eight key species were used for the speed trials (Table 2).

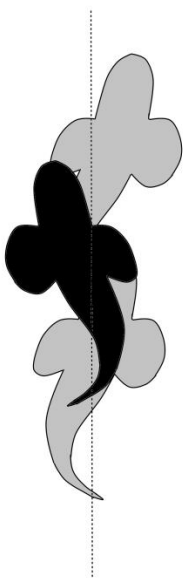
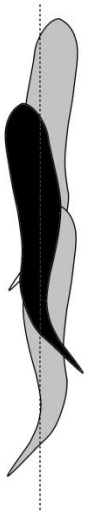
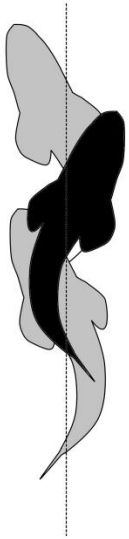
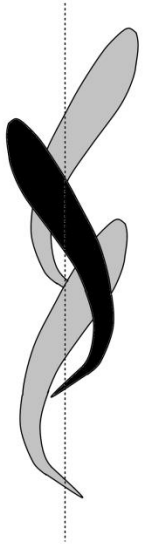
Table 2: Summary of species used in swimming speed estimation including the number of individuals used (*n*), the mean total length (TL; mm) and the length range (mm) for each species.

Scientific name	Common name	*n*	mean TL (mm)	Min - Max TL (mm)
Lepidotrigla mulhalli	Roundsnout gurnard	1	164	164
Parequula melbournensis	Silver biddy	3	171	170-174
Platycephalus bassensis	Sand flathead	10	329	264-427
Thamnaconus degeni	Leatherjacket	10	142	108-187
Trachurus declivis	Jack mackerel	5	259	246-289

5.3.1.1. Stride length

Both *P. melbournensis* and *T. declivis* had narrow yawing (side to side movement of the head relative to forward swimming direction) and small undulations of just the tail. The other three species all had large yawing of the head from side to side and undulations throughout the entire length of the body which suggest a different swimming mode. *Lepidotrigla mulhalli* had the greatest stride length of all the species and *T. degeni* had the smallest (Table 3).

Table 3: The mean measurements of stride length ± SD relative to body length (BL) and silhouette outlines of the movements for each species of interest.

Species	*L. mulhalli*	*P. melbournensis*	*P. bassensis*	*T. degeni*	*T. declivis*
Stride length	0.43 BL*	0.79 ± 0.14 BL	0.68 ± 0.19 BL	0.76 ± 0.24 BL	0.86 ± 0.11 BL
Movement					

* n = 1; the only estimate is provided.

5.3.1.2. Muscle contraction

The muscle contractions of 29 fish from five species were measured. The average minimum muscle contraction time ranged from 16.3 to 23.1 ms in the five species assessed (Table 4). Due to the mortality of individuals, some species had very low replication. *Thamnaconus degeni* had the smallest minimum contraction time but also had the greatest level of error.

Table 4: The average minimum muscle contraction time (Min cont.; ms) ± SD and number of individuals tested for each fish bycatch species.

Species	Min cont. (ms)	SD	n
L. mulhalli	20.4	N/A	1
P. bassensis	23.1	2.84	10
P. melbournensis	16.3	1.41	3
T. declivis	17.0	1.62	5
T. degeni	17.8	5.59	10

5.3.1.3. Maximum swimming speed

The maximum observed speeds, derived from stride length and muscle contraction time, were calculated for each individual, and averaged for each species: *L. mulhalli*, *T. degeni*, *P. melbournensis*, *P. bassensis* and *T. declivis* (Figure 6). The speeds ranged from 1.7 m s^{-1} for *L. mulhalli* to 6.4 m s^{-1} for *T. declivis*.

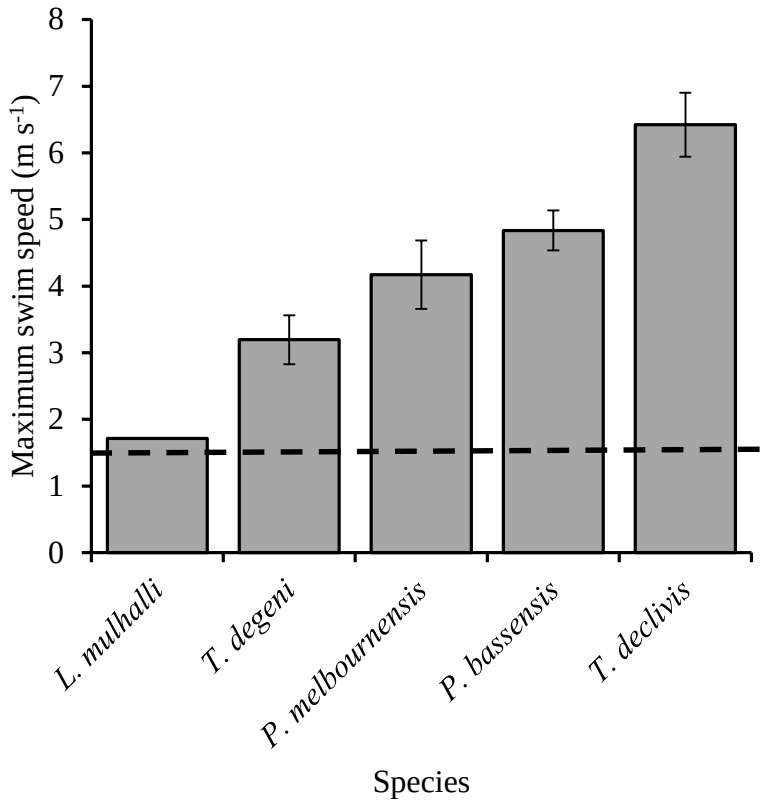


Figure 6: The maximum swimming speeds (m s^{-1}) ± SE calculated for five fish bycatch species of interest from North-Eastern Tasmania. *Due to the low sample size (n = 1) no error bar is provided for *L. mulhalli*. Dashed line indicates mean towing speed of commercial fishing vessel.

5.3.2. Predicting swimming speed from historical data

A total of 255 individual swimming speed measurements of fish species were gathered from 31 different primary literature sources. For the full list of speed estimates and references see Appendix 5.6.1.

5.3.2.1. Swimming modes of fishes

A full range of caudal fin swimmers were identified in the data set. There was an insufficient sample size to include ostraciiform in the analysis (n = 1). Anguilliform, carangiform, subcarangiform and thunniform swimmers were all identified as the predominant caudal fin swimming modes (Table 5). Subcarangiform was the most common mode of caudal fin swimmer for which swimming speeds were available. Anguilliform species had the least data for swimming speed estimates.

Table 5: Summary of the fish species and the number of individual fish of each swimming mode used in the equation to predict maximum swimming speed.

Swim mode	Number of species	Number of individuals
Anguilliform	9	12
Carangiform	18	39
Subcarangiform	39	180
Thunniform	8	26
Total	74	257

5.3.2.2. Caudal fin aspect ratio

Using the historical data for swimming modes and the caudal fin aspect ratio, the minimum, median and maximum aspect ratio for anguilliform, subcarangiform, carangiform and thunniform are provided in Figure 7. Anguilliform had the lowest aspect ratio with values ranging from 0 to 1.61 and thunniform had the greatest aspect ratio with values ranging from 5.5 to 7.9.

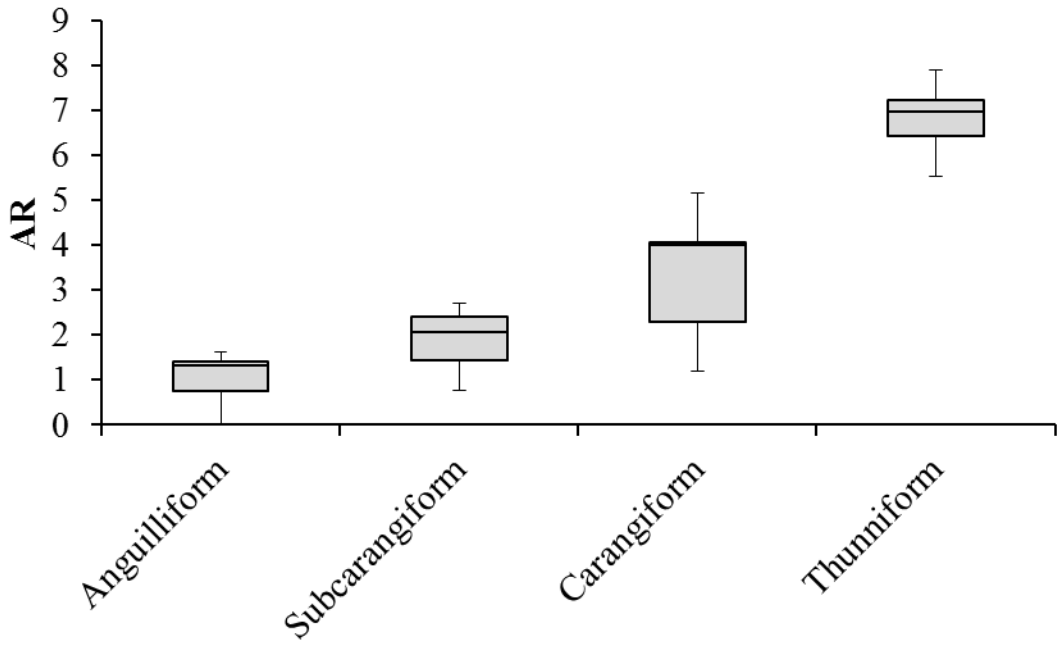


Figure 7: Box plot displaying the minimum, median and maximum caudal fin aspect ratios (AR) and the lower and upper quartiles for each of the caudal fin swimming modes. Data summarised from 31 studies and 255 individuals.

5.3.2.3. Predictive formula

The relationship between caudal fin aspect ratio (AR) and maximum swimming speed of 74 species from the literature was best described by an exponential equation. ($y = 0.595e^{0.4249x}$, R^2 of 0.8524; Figure 8). Most of the data points (80 %) were in the AR range of 0 to 2.9. Each data point was categorised into a swimming mode. There were four outliers (three thunniform species and one subcarangiform species) that had speeds outside the confidence intervals.

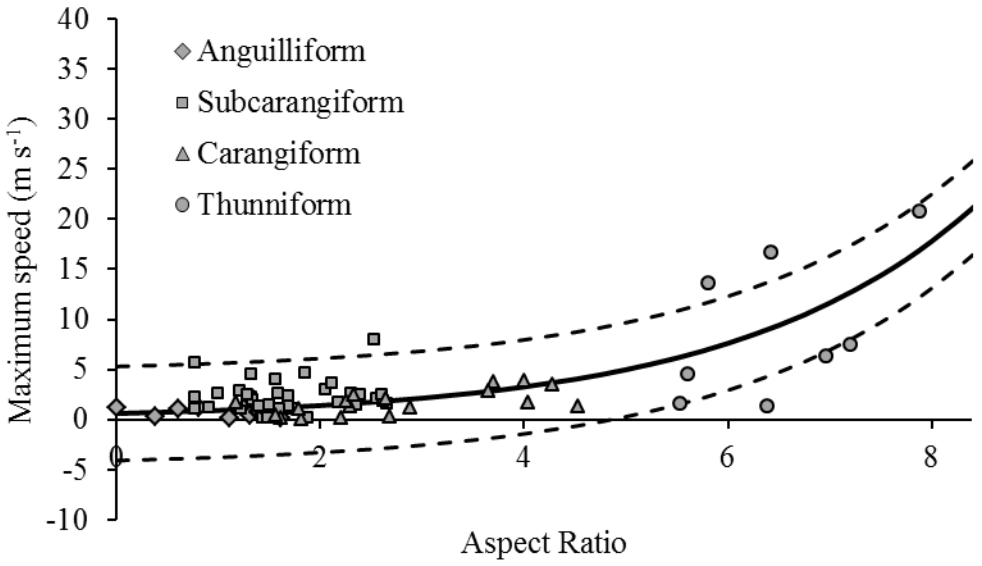


Figure 8: The observed maximum swimming speeds (m s^{-1}) correlated with caudal fin aspect ratio of teleost species collected from historical literature and categorised by swimming mode (indicated by different symbol shapes). The solid line indicates the fitted exponential equation and dotted lines are 5 % and 95% confidence limits.

5.3.3. Validation of predictive formula

5.3.3.1. Swimming mode

All eight of the fish bycatch species of interest in the study were classified by swimming mode and five different modes were observed (Table 6). Initial propulsion and prolonged/sustained swimming was predominantly with the use of the pectoral, dorsal and anal fins, followed by a progression to the predominant use of the caudal fin for maximum swimming activity with *T. degeni.* Therefore, this species was included in the study.

Table 6: The swimming modes of the eight fish bycatch species of interest in this study during maximum swimming speed.

Species	Swimming mode
L. gallus	Anguilliform
L. mulhalli	Subcarangiform
P. bassensis	Subcarangiform
P. melbournensis	Carangiform
N. richardsoni	Subcarangiform
S. flindersi	Subcarangiform
T. declivis	Carangiform
T. degeni	Subcarangiform*

*Uses Diodontiform/Ballistoriform caudal fin movements during prolonged and sustained speeds.

5.3.3.2. Caudal fin aspect ratio

Estimates of AR were calculated for all eight of the species in this study. The two Platycephalidae species and *L. gallus* had the lowest values of AR as a result of the species having flat or rounded tail edges (Table 7 and Figure 9). The highest estimates of AR were for *T. declivis* and *P. melbournensis* which had high concave shaped tails. The area of the tail used to calculate the AR varied depending on the narrowest part of the caudal peduncle and the shape of the fin itself (Figure 9).

Table 7: The mean estimates of caudal fin aspect ratio (AR) ± SE for each of the fish bycatch species of interest. Number of individuals (n).

Species	n	AR	SE
L. gallus	15	0.74	0.008
L. mulhalli	15	1.06	0.017
P. bassensis	11	0.83	0.011
P. melbournensis	9	2.12	0.021
N. richardsoni	10	0.76	0.011
S. flindersi	10	1.05	0.020
T. declivis	10	2.11	0.021
T. degeni	6	0.70	0.044

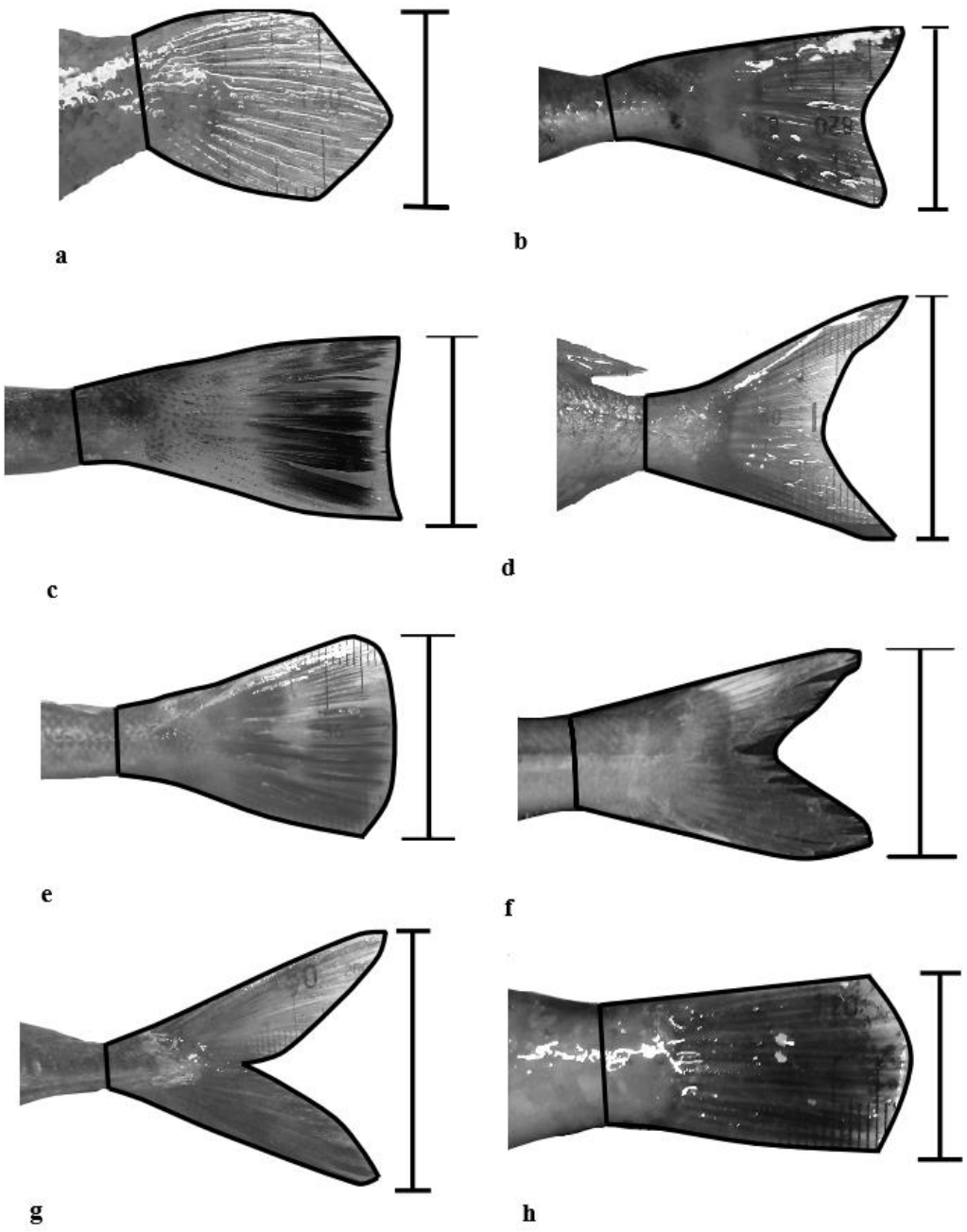


Figure 9: The measurements taken of the caudal fins of the eight fish bycatch species of interest caught in North-Eastern Tasmania. The species include **a**) *L. gallus*, **b**) *L. mulhalli*, **c**) *P. bassensis*, **d**) *P. melbournensis* **e**) *N. richardsoni*, **f**) *S. flindersi*, **g**) *T. declivis*, and **h**) *T. degeni*. The vertical line indicates fin height, and the fin area is shown in outline.

5.3.3.3. Predicted speed

The maximum swim speeds for the 8 species of interest were then predicted using the model developed. Based on AR, there was a smaller range in the predicted maximum speeds for *N. richardsoni*, *T. degeni*, *L. gallus*, *P. bassensis*, *S. flindersi*, and *L. mulhalli* (Figure 11). The lowest predicted speed was 0.8 m $s^{-1}$for *T. degeni* and the highest predicted speed was 1.4 m $s^{-1}$for *T. declivis*.

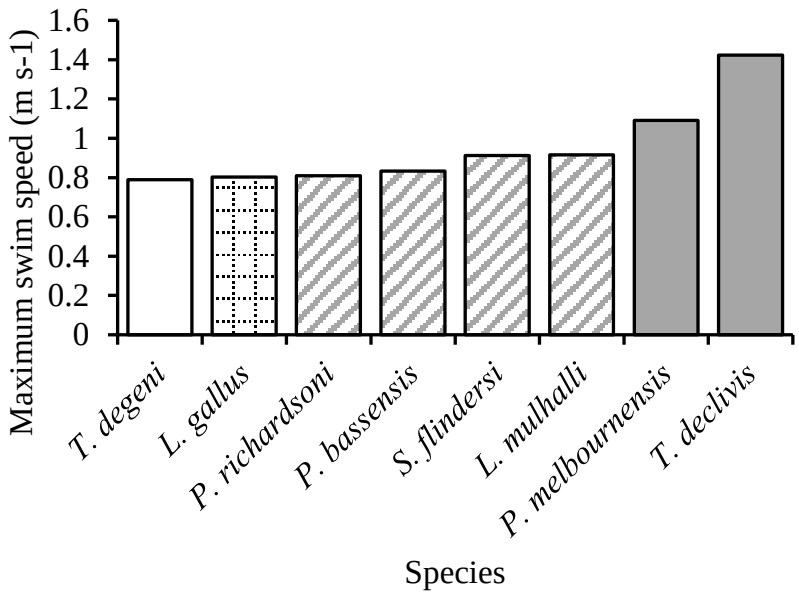


Figure 11: The predicted maximum swimming speeds (m s^{-1}) for each of the eight species of interest caught in North-Eastern Tasmania, determined from the predictive equation based on measured AR. The different bars show the swimming modes: carangiform (solid dark); subcarangiform (diagonal stripes); anguilliform (squares); species with more multiple swimming modes (solid light).

5.3.3.3. Observed versus predicted

For verification of the accuracy of the predictive model, the observed speed values of the 5 species (estimated earlier in this chapter) were compared with the predictive model results. The observed swimming speed estimates calculated for four of the five fish bycatch species of interest were within the mean + 95% confidence limit of the predictive exponential formula from historical data. The species that had the observed value closest to the predicted was *L. mulhalli* (Figure 10). One species, *T. declivis*, was outside the 95 % confidence limit.

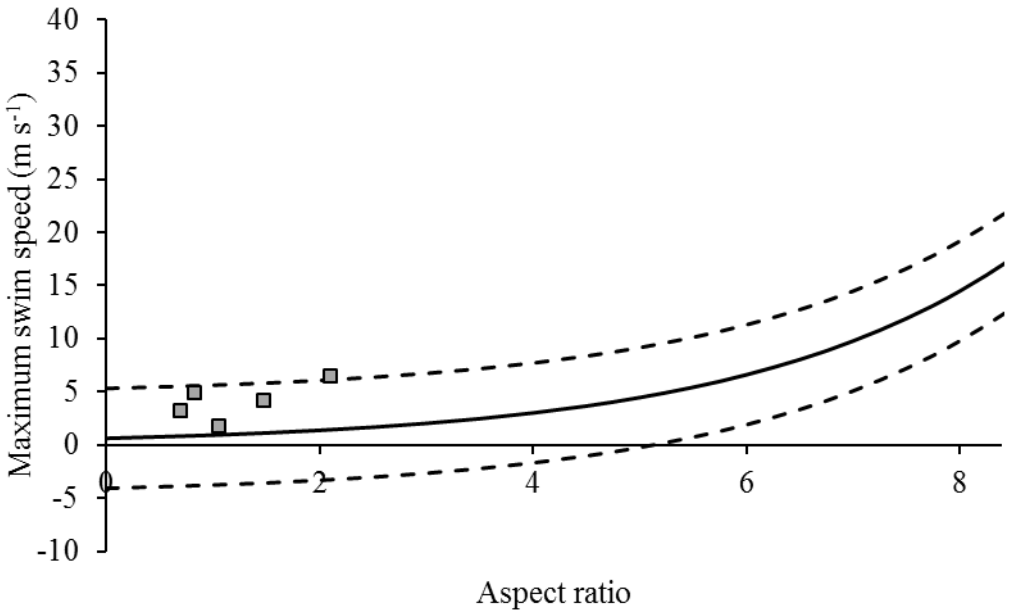


Figure 10: The observed maximum swimming speeds (m s^{-1}) and aspect ratios of the fish bycatch species of interest plotted on the predictive exponential curve (solid line) with 95 % confidence limits (dotted line) derived from other studies.

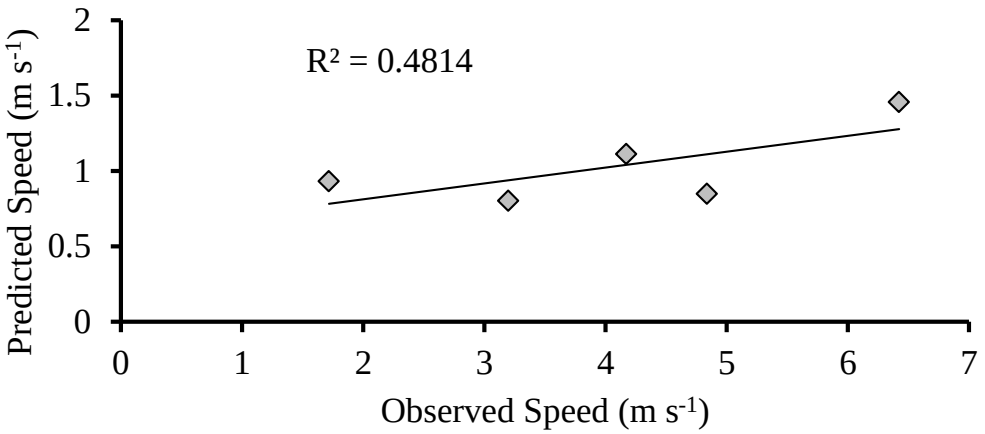


Figure 12: Correlation between the observed and predicted maximum swimming speed of the five species of interest.

5.4. Discussion

An estimate of maximum swimming speed for various bycatch species is invaluable to understanding the effect of using bycatch reduction devices in commercial trawl fisheries. In this study, a wide range of maximum swimming speeds were seen across the five morphologically different species studied in this chapter.

To compare these species with others, not only in North-Eastern Tasmania waters but around the world, the morphology and swimming movements of the fish are examined. The study of a fish's form and motion is important for understanding the swimming capabilities and habitat and/or ecological niche of a species. As well as this, the aspect ratio is intrinsically linked with the swimming mode of the fish species (Fulton *et al.* 2005; Sambilay 1990; Tytell *et al.* 2010). Four of the eight species of interest predominantly use a subcarangiform swimming mode when at maximum swimming speeds. This means they have a greater yawing movement of their head and undulation of their entire body than carangiform and thunniform (Lindsey 1978). This is common in species that have a long body and a rounded tail (Lindsey 1978). The *Platycephalus* species and *L. mulhalli* are benthic species that are morphologically suited to living on the seabed (Edgar 2008). They are adapted to short bursts of movement for feeding and escaping predators and do not require the muscle structure for long sustained swimming (Lindsey 1978). Although *T. degeni* predominantly displayed a combination of Diodontiform and Ballistiform when prolonged/sustained swimming, when stimulated they used subcarangiform caudal fin movements during bursts of maximum speed in this study. This was also observed in a study of triggerfish, *Rhinecanthus aculeatus* (Loofbourrow 2009). On the other hand, *T. declivis* and *P. melbournensis* were both carangiform swimmers. They are schooling species and are adapted to vertical migration which means they tend to swim at higher speeds for long periods of time (Beamish 1978). *Lophonectes gallus* was classified as an anguilliform swimmer. This benthic species, like the *Platycephalus* species and *L. mulhalli*, generally rests and waits on the seabed and is not capable of fast movements for long periods of time (Gerking 1994).

From an initial observation of body shape, it would be expected that not all eight species of fish would have the same maximum shape and movement and therefore they would have different swimming capabilities. It was initially predicted that the pelagic stream-lined species, *T. declivis*, would have the fastest swimming speeds and perhaps the flatfish, *L. gallus*, would be less adapted to fast movements. In this study the method for calculating the

maximum speed of the fish required the calculation of stride length and muscle contraction time. The variation in these two factors affects the overall estimate of speed. For two of the species examined, the stride lengths estimated were similar to those reported in other studies. Yanase and Arimoto (2007) found that, for a 300 mm individual, the average stride length of sand flathead was 0.64 BL, compared with 0.68 BL for a 330 mm fish in this study. For *T. declivis*, this study's estimate of 0.86 BL for a 260 mm individual was larger than the estimates found for its Japanese counterpart. Riyanto *et al.* (2014) found that a 180 mm *T. japonicus* in 22°C water has a stride length of 0.75 BL. It is found that the distance covered in one stride would increase in larger fish due to the larger span of the caudal fin and caudal tail-beat amplitude (He and Wardle 2005; Yanase and Arimoto 2007). There have been no studies done on the stride lengths on *T. degeni*, *P. melbournensis*, *L. mulhalli* or related species.

There are only two other studies that have reported on the minimum muscle contraction times of species similar to those in this study. Yanase *et al.* (2007) observed the contraction of muscle in different sized *P. bassensis* subjected to different water temperatures. They found that in 15 °C water, small individuals of around 220 mm had minimum contraction times of 18 ms in 15 °C while both medium to larger individuals (270 – 430 mm fish) had contraction times of 20 ms (Yanase *et al.* 2007). This study found that the mean muscle contraction of *P. bassensis* in 16 °C water was slightly larger with a value of 23 ms for individuals of around 330 mm. Conversely, the estimate for *T. declivis* of 17 ms for a 260 mm fish found in this study was much lower than that of the *T. japonicus*, which produced an estimate of 23 ms for an unexercised fish of about 180 mm in length (Riyanto *et al.* 2014). It is agreed that muscle contraction time in fish increases with increasing total fish length as the muscle blocks themselves become larger (Wardle 1975; Wardle *et al.* 1989; Yanase *et al.* 2007). There were no other similar studies to compare the muscle contraction results of the other three species studied, *T. degeni*, *P. melbournensis* and *L. mulhalli*. One of the main external factors that affect the contraction of the muscle includes the position along the body and the temperature of the water (Riyanto *et al.* 2014; Wardle 1980; Yanase *et al.* 2007). The temperature of the water during sampling in this study was between 15 and 16 °C and, as such, the results were only compared with those studies with corresponding temperatures.

The fastest fish in this study were *T. declivis* and *P. bassensis*. The maximum speed estimated for 330 mm *P. bassensis* was 4.83 m s^{-1}, 20% faster than that reported for the same species by Yanase *et al.* (2007) who estimated that a 300 mm fish would swim at 4 m s^{-1} using a similar

method. Yanase *et al.* (2009) found that larger fish were slower, with the estimated speed of 2.3 m s^{-1} for a 400 mm fish. The maximum speed estimates for *T. declivis* (6.42 m s^{-1}) in this study were greater than that of similar species such as Japanese mackerel, *T. japonicus* (2.29 m s^{-1}). It must be acknowledged that the observed speeds in this study may not accurately reflect the actual achievable maximum speeds of the fish. While sampling, it was difficult to keep many of the individuals alive. It is suggested that certain components of the sampling had an impact on the quality and survivability of the fish. These include the capture process of trawling, the handling of fish on the back deck as well as the alien environment in which the fish were contained. Therefore, this demonstrates some of the issues with attempting to gather data from bycatch species while at sea.

The morphology of a fish is recognised to be a strong indicator of swimming ability (He and Wardle 2005). Fin aspect ratio is in fact intrinsically linked to the swimming ability of fish species for both pectoral fin swimmers (Fulton *et al.* 2005) and caudal fin swimmers (Fisher and Hogan 2007; He and Wardle 2005; Sambilay 1990). The greatest mean estimate of aspect ratio was found for *T. declivis* and *P. melbournensis*. This was to be expected as they are both carangiform swimmers. In this study *T. declivis* had an AR estimate of 2.1. Similar species, such as *T. mediterraneus* and *T. symmetricus* have aspect ratios of 3.6 and 4.3, respectively (Sambilay 1990). This study estimated an AR of 2.2 for *P. melbournensis* which is higher than a previous estimate of 1.29 but similar to other species in the *Gerres* genus (Froese and Pauly 2014). The lowest estimate was found for *T. degeni* and *L. gallus*. Both of these species have much thicker caudal peduncles and rounded caudal fin edges. The AR ratio for *L. gallus*, 0.74, found in this study was only slightly less than that of an earlier estimate, 0.94 (Froese and Pauly 2014). However, such a low estimate is typical for flatfish species with a rounded caudal fin as can be seen with *Arnoglossus aspilos* (0.90), *A. laterna* (0.77), and *A. polyspilus* (0.69) (Froese and Pauly 2014). Aspect ratios have been linked to the caudal fin swimming modes in Lindsey (1978) but this study is the first to produce a range of estimates for each classification. Using estimates from 74 species, mean ARs for each of the swimming mode categories now exist.

The next step is to understand the link between swimming mode and aspect ratio as well as the effect on the maximum swimming speed of a fish. There was a strong exponential relationship between the caudal fin aspect ratio and maximum swimming speed from published data compiled and analysed in this study. The anguilliform species, with their low estimates of aspect ratio had the lowest speeds while the high aspect ratios of the thunniform

were the fastest. The line of best fit for this data was in the form of an exponential curve and this allows us to make general predictions as to the maximum swimming speed of a fish given the aspect ratio of the caudal fin. Since the shape of the fin is linked to its swimming mode, even classifying the fish by the way it swims provides a rudimentary estimate of maximum speed. Benthic species that are lie-and-wait predators are often subcarangiform and, as seen in this study, had low aspect ratios to match their maximum speeds of around 1 to 5 m s^{-1}. The higher aspect ratios that are associated with tall, curved caudal fins were found in the thunniform species that could travel up to 20 m s^{-1}. The size and shape of the caudal fins is adapted to suit their behaviour in a specific ecological niche, for example chasing/pursuing prey, escape from predators, migration, schooling, foraging (prey search), and reproduction (Videler 1993).

The confidence limits around the predicted curve are quite large and provide that the predicted speed of anguilliform, with a small or no caudal fin, could obtain up to 5 m s^{-1}. On the other end of the scale, a thunniform species with an aspect ratio of 8 could have speeds between 13 and 22 m s^{-1}. The general trend of the increasing speed with increasing caudal fin aspect ratio is an important correlation that allows for estimating the approximate speed of fish based on morphometrics alone. This model, however, provides a generalised estimation that can be used for comparing species. It also demonstrates the strength of the relationship between a morphometric measurement and the maximum speed a fish. This adds weight to the widely held view that a species body shape and physiology relates back to its habitat and swimming activity (Fulton *et al.* 2005; Sambilay 1990; Webb 1984).

The variation in maximum swimming speeds of the historical data could be attributed to a number of factors including water temperature (Beamish 1978; Joaquim *et al.* 2004; Yanase *et al.* 2007), fish size (Bainbridge 1958a; Beamish 1978), accuracy of measurements, and technological development of experimental methods (Beamish 1978). The temperature of the water is known to affect the maximum speeds of fish. This is due to the restrictions on the contraction of the muscle whereby the cold water causes muscle to use less energy and therefore is less efficient (Videler 1993). Within a particular species, increasing fish size increases the maximum swimming speed of a fish due to the larger muscle blocks and fin size (Beamish 1978; He *et al.* 2013). For a given species of fish, different lengths will show great variability in not only maximum speed but also swimming duration. For the ease of comparison between species and for comparisons with trawl speeds, the maximum swim speed of the average fish size was used to represent a species rather than the use of body

lengths per second (BL/S). This makes the results presented here more applicable to the fishing industry and comparable to the speed of a moving trawl.

The technique for measuring aspect ratio and the technology used to measure swimming speed, has changed over time for example the use of image analysis software has only been available for the last couple of decades and allows for more accurate measurements (Bainbridge 1958b; Riyanto *et al.* 2014). All of these factors are likely to impact upon the reliability of the mean speed and aspect ratio of the historical studies. It was seen that the correlation between the observed and predicted swimming speeds presented in this study provided a correlation coefficient of only 0.48. This means that similar values of swimming speed were not achieved from both observed and predicted methods. It is likely that the speeds measured from the individuals measured from the trawl net are incorrect due to the limitations mentioned previously.

Few other studies have used historical data to predict swimming speed from a morphometric measurement such as caudal fin aspect ratio (Sambilay 1990). There have been previous attempts to look at the correlation between maximum swimming speed and aspect ratio within a family or species of fish. For example, Fulton *et al.* (2005) found a strong correlation between the pectoral fin aspect ratio and maximum swimming speed. Sambilay (1990) also used historical data (prior to 1990) to estimate the speeds of fish given the caudal fin aspect ratio and size of a fish across a range of species. Their research found that 77 % of the variation in speed was explained by fish length, aspect ratio and swimming mode (Sambilay 1990). This study builds on the work of (Sambilay 1990) to include the most recent data as well as historical data that was missed. This data set has also been refined to include only maximum or burst speed estimates providing the first study to correlate caudal fin aspect ratio in fish with different swimming modes, with their maximum speed.

This study's finding can be applied beyond these species as the data used to produce the predictive curve includes a range of different species from around the world. The ability for a fish to escape a towed gear, such as a trawl net, is impacted by the speed at which it can swim and the escape path of an approaching net. Many bycatch reduction devices have been designed around the behaviour and swimming abilities of certain species. The knowledge of the maximum swimming speeds of fish could be utilised for the design of bycatch reduction devices or refinement of existing gears/modifications. For example, the use of light as a bycatch reduction device uses LED light to illicit a negative phototactic response and increase the chance of fish avoiding the trawl net. For this to work however, knowledge of

the maximum speeds of each bycatch species that encounters the net is needed for the design of the light in terms of the light intensity and the direction it is facing. Based on the results of this study the species with the greatest swimming speed and therefore with the greatest chance of avoiding an oncoming trawl was *T. declivis*. In the next chapter these data will be combined with the potential visual acuity data from chapter 4 to examine the correlation between the physiology of the fish and its catch rates when caught with artificial light.

5.5. References

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5.6. Appendices

Appendix 5.6.1: Raw swimming speed data of each individual fish used in the chapter including the associated reference. Note: the asterisk denote aspect ratio values that were taken from Froese and Pauly (2014).

Species	Common name	Swimming mode	Length (SL, cm)	Aspect ratio	Speed type	Speed (m/sec)	Source
Abramis brama	Freshwater bream	Subcarangiform	24	1.728	Burst	1.0	(Sambilay 1990)
Acanthocybium solandri	Wahoo	Thunniform	0	6.422	Burst	21.4	(Block *et al.* 1992)
Acanthocybium solandri	Wahoo	Thunniform	89.8	6.422	Burst	12.0	(Sambilay 1990)
Acanthocybium solandri	Wahoo	Thunniform	97.6	6.422	Burst	12.1	(Sambilay 1990)
Acanthocybium solandri	Wahoo	Thunniform	110.2	6.422	Burst	21.3	(Sambilay 1990)
Alburnus alburnus	Bleak	Subcarangiform	5	1.42*	Burst	0.5	(Bainbridge 1958a)
Alosa aestivalis	Blueback herring	carangiform	22.1	2.9*	Burst	1.1	(Castro-Santos 2005)
Alosa fallax	Twaite shad	carangiform	29.3	4.05*	Burst	1.6	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.8	4.05*	Burst	0.9	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	35.6	4.05*	Burst	1.8	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	33.4	4.05*	Burst	1.4	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	39	4.05*	Burst	1.9	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.4	4.05*	Burst	2.5	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.6	4.05*	Burst	2.4	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	33.4	4.05*	Burst	1.9	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.8	4.05*	Burst	1.0	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	35.6	4.05*	Burst	2.0	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.4	4.05*	Burst	1.9	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	30.6	4.05*	Burst	1.8	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	39	4.05*	Burst	1.4	(Clough *et al.* 2004)
Alosa fallax	Twaite shad	carangiform	37	4.05*	Burst	1.5	(Clough *et al.* 2004)
Alosa pseudoharengus	Alewife	Subcarangiform	23.7	2.055	Burst	1.2	(Castro-Santos 2005)
Alosa pseudoharengus	Alewife	Subcarangiform	28.4	2.055	Burst	4.8	(Sambilay 1990)
Alosa sapidissima	American shad	carangiform	41.8	2.3*	Burst	1.3	(Castro-Santos 2005)

Anguilla anguilla	Eel	Anguilliform	60	0*	Maximum	1.1	(Blaxter and Dickson 1959)
Archosargus probatocephalus	Sheepshead porgy	Subcarangiform	29	1.44*	Maximum	0.1	(Steele and Scarfe 1998)
Arius felis	Hardhead sea catfish	Subcarangiform	27	1.88*	Maximum	0.2	(Steele and Scarfe 1998)
Carassius auratus	Goldfish	Subcarangiform	4	1.477	Burst	0.3	(Bainbridge 1958a)
Carassius auratus	Goldfish	Subcarangiform	7	1.477	Burst	0.7	(Bainbridge 1958a)
Carassius auratus	Goldfish	Subcarangiform	9	1.477	Burst	0.6	(Bainbridge 1958a)
Carassius auratus	Goldfish	Subcarangiform	15	1.477	Burst	0.9	(Bainbridge 1958a)
Carassius auratus	Goldfish	Subcarangiform	22	1.477	Burst	0.8	(Bainbridge 1958a)
Carassius auratus	Goldfish	Subcarangiform	6	1.477	Burst	0.8	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	9	1.477	Burst	1.1	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	9	1.477	Burst	1.2	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	13	1.477	Burst	1.3	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	13	1.477	Burst	1.1	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	14	1.477	Burst	1.4	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	16	1.477	Burst	1.9	(Bainbridge 1960)
Carassius auratus	Goldfish	Subcarangiform	7	1.477	Burst	0.7	(Sambilay 1990)
Carassius auratus	Goldfish	Subcarangiform	12.5	1.477	Burst	1.6	(Sambilay 1990)
Carassius auratus	Goldfish	Subcarangiform	13	1.477	Burst	1.7	(Sambilay 1990)
Carassius auratus	Goldfish	Subcarangiform	13	1.477	Burst	2.0	(Sambilay 1990)
Carassius auratus	Goldfish	Subcarangiform	28	1.477	Maximum	0.1	(Steele and Scarfe 1998)
Catostomus commersonii	White sucker	subcarangiform	39	1.59*	Burst	2.6	(Castro-Santos 2005)
Clupea harengus	Sprat	carangiform	8	1.58*	Maximum	0.4	(Blaxter and Dickson 1959)
Clupea harengus	Sprat	carangiform	10	1.58*	Maximum	0.2	(Blaxter and Dickson 1959)
Clupea harengus	Sprat	carangiform	12	1.58*	Maximum	0.6	(Blaxter and Dickson 1959)
Clupea harengus	Atlantic herring	Carangiform	25	2.26*	Burst	1.7	(Sambilay 1990)
Cyprinus carpio	Common carp	Subcarangiform	13	2.176	Burst	1.6	(Bainbridge 1958a)
Cyprinus carpio	Common carp	Subcarangiform	13.5	2.176	Burst	1.7	(Sambilay 1990)
Cyprinus carpio	Common carp	Subcarangiform	10	2.176	Maximum	1.2	(Tudorache *et al.* 2007)
Cyprinus carpio	Common carp	Subcarangiform	19.8	2.176	Maximum	1.6	(Tudorache *et al.* 2007)
Cyprinus carpio	Common carp	Subcarangiform	26.2	2.176	Maximum	2.0	(Tudorache *et al.* 2007)
Dicentrarchus labrax	European sea bass	Subcarangiform	117	1.22*	Maximum	1.1	(Claireaux *et al.* 2006)
Engraulis encrasicolus	European anchovy	carangiform	12.1	1.19*	Maximum	1.6	(Komarov 1971)

Engravlis mordax	Californian anchovy	Carangiform	3.7	2.69*	Burst	0.3	(Sambilay 1990)
Esox lucius	Northern pike	Subcarangiform	16.1	2.35	Burst	2.1	(Sambilay 1990)
Esox lucius	Northern pike	Subcarangiform	20	2.35	Burst	1.5	(Sambilay 1990)
Esox lucius	Northern pike	Subcarangiform	44	2.35	Burst	2.9	(Sambilay 1990)
Euthynnus affinis	Kawakawa	Thunniform	40	5.611	Burst	4.0	(Sambilay 1990)
Euthynnus affinis	Kawakawa	Thunniform	40	5.611	Burst	5.0	(Sambilay 1990)
Gadus morhua	Atlantic cod	Subcarangiform	51	0.769*	Burst	2.8	(Martinez *et al.* 2004)
Gadus morhua	Atlantic cod	Subcarangiform	33	0.769*	Maximum	0.3	(Peck *et al.* 2006)
Gadus morhua	Atlantic cod	Subcarangiform	9	0.769*	Maximum	0.1	(Peck *et al.* 2006)
Gadus morhua	Atlantic cod	Subcarangiform		0.769*	Burst	0.8	(Webber *et al.* 2001)
Gadus morhua callerius	Atlantic cod	Subcarangiform	56	0.769*	Burst	2.1	(Sambilay 1990)
Hypophthalmichthys motitrix	Silver carp	Subcarangiform	27	2.6*	Maximum	2.5	(Komarov 1971)
Ictalurus punctatus	Channel catfish	Subcarangiform	34	1.49*	Maximum	0.1	(Steele and Scarfe 1998)
Katsuwonus pelamis	Skipjack tuna	Thunniform	48	6.969	Burst	6.9	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	48.4	6.969	Burst	9.5	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	48.4	6.969	Burst	7.5	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	57	6.969	Burst	5.9	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	64	6.969	Burst	5.6	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	79	6.969	Burst	6.4	(Sambilay 1990)
Katsuwonus pelamis	Skipjack tuna	Thunniform	50	6.969	Maximum	2.3	(Syme and Shadwick 2002)
Lagodon rhomboïdes	Pinfish	carangiform	15	2.22*	Maximum	0.1	(Steele and Scarfe 1998)
Lepomis macrochiru	Bluegill sunfish	carangiform	15	1.62*	Maximum	0.1	(Steele and Scarfe 1998)
Leuciscus leuciscus	Common dace	Subcarangiform	5	1.286	Burst	0.9	(Bainbridge 1958a)
Leuciscus leuciscus	Common dace	Subcarangiform	9	1.286	Burst	1.6	(Bainbridge 1958a)
Leuciscus leuciscus	Common dace	Subcarangiform	17	1.286	Burst	2.2	(Bainbridge 1958a)
Leuciscus leuciscus	Common dace	Subcarangiform	24	1.286	Burst	2.2	(Bainbridge 1958a)
Leuciscus leuciscus	Common dace	Subcarangiform	20	1.286	Burst	2.2	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	21	1.286	Burst	2.4	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	10	1.286	Burst	1.1	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	10	1.286	Burst	1.3	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	14	1.286	Burst	1.6	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	15	1.286	Burst	1.8	(Bainbridge 1960)

Leuciscus leuciscus	Common dace	Subcarangiform	16	1.286	Burst	2.0	(Bainbridge 1960)
Leuciscus leuciscus	Common dace	Subcarangiform	9.2	1.286	Burst	1.6	(Sambilay 1990)
Leuciscus leuciscus	Common dace	Subcarangiform	18.1	1.286	Burst	1.7	(Sambilay 1990)
Leuciscus leuciscus	Common dace	Subcarangiform	20	1.286	Burst	2.5	(Sambilay 1990)
Leuciscus rutilus	Common roach	Subcarangiform	24	1.686	Burst	1.3	(Sambilay 1990)
Makaira nigricans	Blue marlin	Thunniform	0	7.89*	Burst	20.8	(Block *et al.* 1992)
Melanogrammus aeglefinus	Haddock	Subcarangiform	9.5	1.325	Burst	2.6	(Sambilay 1990)
Melanogrammus aeglefinus	Haddock	Subcarangiform	42	1.325	Burst	1.8	(Sambilay 1990)
Merlangius merlangus	Whiting	Subcarangiform	15.2	0.903	Burst	1.5	(Sambilay 1990)
Merlangius merlangus	Whiting	Subcarangiform	20	0.903	Burst	1.6	(Sambilay 1990)
Merlangius merlangus	Whiting	Subcarangiform	30.5	0.903	Maximum	0.5	(Steinhausen *et al.* 2005)
Morone saxatiis	Striped bass	Subcarangiform	50	2.309	Burst	2.6	(Castro-Santos 2005)
Mugil auratus	Golden grey mullet	Subcarangiform	21.9	1.325	Burst	4.5	(Sambilay 1990)
Mugil cephalus	Flathead grey mullet	Subcarangiform	3.5	2.549	Burst	0.7	(Sambilay 1990)
Mugil cephalus	Flathead grey mullet	Subcarangiform	21	2.549	Burst	4.3	(Sambilay 1990)
Mugil cephalus	flathead grey mullet	Subcarangiform	39.5	2.549	Maximum	1.4	(Vagner *et al.* 2008)
Mugil saliens	Leaping mullet	Subcarangiform	17.9	1.556	Burst	4.0	(Sambilay 1990)
Oncorhynchus keta	Chum salmon	Subcarangiform	70.5	2.65*	Maximum	1.5	(Tanaka *et al.* 2001)
Oncorhynchus keta	Chum salmon	Subcarangiform	65	2.65*	Maximum	1.7	(Tanaka *et al.* 2001)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	57	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	55	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	62	2.39*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	52	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	68	2.39*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	44	2.39*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	50	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	51	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	44	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	48	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform		2.39*	Maximum	1.7	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	58	2.39*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	44	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)

Oncorhynchus kisutch	Silver salmon	Subcarangiform	67	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	67	2.39*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	65	2.39*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	64	2.39*	Maximum	1.7	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	51	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	36	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	67	2.39*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	56	2.39*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	61	2.39*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	53	2.39*	Maximum	3.2	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	66	2.39*	Maximum	3.2	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	58	2.39*	Maximum	3.7	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	76	2.39*	Maximum	3.3	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	51	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	46	2.39*	Maximum	2.8	(Weaver 1963)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	36	2.39*	Maximum	3.3	(Weaver 1963)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	61	2.39*	Maximum	5.2	(Weaver 1963)
Oncorhynchus kisutch	Silver salmon	Subcarangiform	61	2.39*	Maximum	5.3	(Weaver 1963)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	4	1.686	Burst	0.7	(Bainbridge 1958a)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	13	1.686	Burst	2.2	(Bainbridge 1958a)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	29	1.686	Burst	3.2	(Bainbridge 1958a)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	10	1.686	Burst	1.0	(Bainbridge 1960)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	15	1.686	Burst	1.8	(Bainbridge 1960)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	28	1.686	Burst	3.5	(Bainbridge 1960)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	68	1.686	Burst	1.2	(Kawabe *et al.* 2004)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	59	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	66	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	68	2.39*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	64	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	62	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	59	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	63	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)

Oncorhynchus mykiss	Steelhead trout	Subcarangiform	67	2.39*	Maximum	2.2	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	67	2.39*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	63	2.39*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	61	2.39*	Maximum	4.2	(Weaver 1963)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	71	2.39*	Maximum	5.3	(Weaver 1963)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	76	2.39*	Maximum	7.4	(Weaver 1963)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	61	2.39*	Maximum	8.0	(Weaver 1963)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	81	2.39*	Maximum	5.7	(Weaver 1963)
Oncorhynchus mykiss	Steelhead trout	Subcarangiform	61	2.39*	Maximum	7.1	(Weaver 1963)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	29	1.686	Burst	6.0	(Webb 1971)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	29	1.686	Burst	7.0	(Webb 1971)
Oncorhynchus mykiss	Rainbow trout	Subcarangiform	29	1.686	Burst	8.0	(Webb 1971)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	63	2.701	Maximum	2.7	(Hinch and Bratty 2000)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	64	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	61	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	66	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	58	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	64	2.61*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	76	2.61*	Maximum	2.1	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	65	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	64	2.61*	Maximum	1.9	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	70	2.61*	Maximum	1.7	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	63	2.61*	Maximum	1.7	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	62	2.61*	Maximum	2.0	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	65	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	55	2.61*	Maximum	1.7	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	59	2.61*	Maximum	1.8	(Paulik and DeLacy 1957)
Oncorhynchus nerka	Sockeye Salmon	Subcarangiform	69	2.61*	Maximum	1.6	(Paulik and DeLacy 1957)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	19.9	2.477	Burst	0.6	(Sambilay 1990)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	31.5	2.477	Burst	0.7	(Sambilay 1990)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	51	1.64*	Maximum	5.3	(Weaver 1963)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	71	1.64*	Maximum	5.5	(Weaver 1963)

Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	81	1.64*	Maximum	6.1	(Weaver 1963)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	81	1.64*	Maximum	6.5	(Weaver 1963)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	71	1.64*	Maximum	5.8	(Weaver 1963)
Oncorhynchus tshawytscha	Chinook salmon	Subcarangiform	97	1.64*	Maximum	6.6	(Weaver 1963)
Orthopristis chrysoptera	Pigfish	carangiform	18	1.83*	Maximum	0.1	(Steele and Scarfe 1998)
Paralichthys olivaceus	Japanese flounder	Anguilliform	51.8	1.31*	Maximum	0.4	(Kawabe *et al.* 2004)
Paralichthys olivaceus	Japanese flounder	Anguilliform	52.2	1.31*	Maximum	0.4	(Kawabe *et al.* 2004)
Perca fluviatilis	Perch	Subcarangiform	11.5	1.52*	Maximum	1.5	(Komarov 1971)
Perca fluviatilis	European perch	Subcarangiform	24	1.48	Burst	1.3	(Sambilay 1990)
Petromyzon marinus	Sea lamprey	Anguilliform	37	0.81*	Burst	1.2	(Nursall 1962)
Pholis gunnellus	Butterfish	Anguilliform	10	0.38*	Maximum	0.3	(Blaxter and Dickson 1959)
Platycephalus bassensis	Sand flathead	Subcarangiform	20.9	1*	Maximum	3.3	(Yanase *et al.* 2007)
Platycephalus bassensis	Sand flathead	Subcarangiform	29.1	1*	Maximum	2.6	(Yanase *et al.* 2007)
Platycephalus bassensis	Sand flathead	Subcarangiform	40.7	1*	Maximum	2.0	(Yanase *et al.* 2007)
Pleuronectes flesus	Flounder	Anguilliform	27.5	0.61*	Maximum	1.1	(Blaxter and Dickson 1959)
Pleuronectes limanda	Dab	Anguilliform	7	1.11*	Maximum	0.1	(Blaxter and Dickson 1959)
Pleuronectes platessa	Plaice	Anguilliform	22	1.4*	Maximum	0.7	(Webb 2002)
Plueronectes microcephalus	Lemon sole	Anguilliform	8	1.61*	Maximum	0.2	(Blaxter and Dickson 1959)
Plueronectes platessa	Plaice	Anguilliform	8	1.4*	Maximum	0.3	(Blaxter and Dickson 1959)
Plueronectes platessa	Plaice	Anguilliform	15	1.4*	Maximum	0.9	(Blaxter and Dickson 1959)
Plueronectes platessa	Plaice	Anguilliform	25	1.4*	Maximum	1.3	(Blaxter and Dickson 1959)
Pollachius virens	Saithe	Subcarangiform	21	1.296	Burst	2.0	(Sambilay 1990)
Pollachius virens	Saithe	Subcarangiform	43.1	1.296	Burst	3.0	(Sambilay 1990)
Pollachius virens	Saithe	Subcarangiform	34.6	1.296	Maximum	0.9	(Steinhausen *et al.* 2005)
Pollachius virens	Saithe	Subcarangiform	25	1.296	Burst	2.2	(Videler 1993)
Pollachius virens	Saithe	Subcarangiform	50	1.296	Burst	3.3	(Videler 1993)
Pomotomus salatrix	Bluefish	carangiform	16	2.66*	Maximum	2.0	(Komarov 1971)
Ptychocheilus grandis	Sacramento pikeminnow	subcarangiform	75	0.77*	Burst	4.8	(Bainbridge 1958a)
Ptychocheilus grandis	Sacramento pikeminnow	subcarangiform	75	0.77*	Burst	6.0	(Bainbridge 1958a)
Ptychocheilus grandis	Sacramento pikeminnow	subcarangiform	80	0.77*	Burst	6.7	(Bainbridge 1958a)
Ptychocheilus grandis	Sacramento pikeminnow	subcarangiform	85	0.77*	Burst	4.9	(Bainbridge 1958a)
Salmo irideus	Rainbow trout	Subcarangiform	12.6	1.686	Burst	2.2	(Sambilay 1990)

Salmo irideus	Rainbow trout	Subcarangiform	20	1.686	Burst	1.7	(Sambilay 1990)
Salmo irideus	Rainbow trout	Subcarangiform	29.2	1.686	Burst	2.9	(Sambilay 1990)
Salmo trutta	Sea trout	Subcarangiform	24	1.206	Burst	2.4	(Sambilay 1990)
Salmo trutta	Sea trout	Subcarangiform	38	1.206	Burst	3.3	(Sambilay 1990)
Sander lucioperca	Pike-perch	Subcarangiform	44	1.329	Burst	1.9	(Sambilay 1990)
Sander vitreus	Walleye	Subcarangiform	32	1.29*	Burst	2.5	(Castro-Santos 2005)
Sarda chiliensis	Pacific bonito	Carangiform	57	3.706	Burst	3.7	(Sambilay 1990)
Sarda sarda	Atlantic bonito	Carangiform	14.9	4.538	Burst	1.3	(Sambilay 1990)
Scardinius erythropthalmus	Rudd	Subcarangiform	19	2.353	Burst	1.1	(Bainbridge 1958a)
Scardinius erythropthalmus	Rudd	Subcarangiform	22	2.353	Burst	1.3	(Sambilay 1990)
Scardinius erythropthalmus	Rudd	Subcarangiform	22.3	2.353	Burst	1.3	(Sambilay 1990)
Scardinius erythropthalmus	Rudd	Subcarangiform	24	2.353	Burst	1.7	(Sambilay 1990)
Scomber japonica	Chub mackerel	Carangiform	30.5	4.008*	Burst	5.5	(Sambilay 1990)
Scomber japonica	Chub mackerel	Carangiform	33.4	4.008*	Burst	3.0	(Sambilay 1990)
Scomber japonica	Chub mackerel	Carangiform	38	4.008*	Burst	3.0	(Sambilay 1990)
Scomber japonica	Chub mackerel	Carangiform	27.1	5.157*	Burst	2.3	(Sambilay 1990)
Scomber scombrus	Atlantic mackerel	Carangiform	30	4.008	Burst	5.4	(Sambilay 1990)
Scomber scombrus	Atlantic mackerel	Carangiform	33	4.008	Burst	3.0	(Sambilay 1990)
Scomber scombrus	Atlantic mackerel	Carangiform	38	4.008	Burst	3.0	(Sambilay 1990)
Sebastes mystinus	Blue rockfish	Subcarangiform	15.1	1.6	Burst	1.1	(Sambilay 1990)
Sphyraena barracuda	Barracuda	Subcarangiform	122	2.51*	Maximum	12.0	(Gero 1952b)
Sphyraena barracuda	Barracuda	Subcarangiform	130	2.51*	Maximum	12.0	(Gero 1952b)
Sphyraena barracuda	Great barracuda	Subcarangiform	129.5	2.556	Burst	3.8	(Nursall 1962)
Sphyraena barracuda	Great barracuda	Subcarangiform	17	2.556	Burst	3.8	(Sambilay 1990)
Sprattus sprattus	European sprat	Carangiform	7.6	1.805	Burst	1.4	(Sambilay 1990)
Sprattus sprattus	European sprat	Carangiform	12	1.805	Burst	0.6	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	67	7.212	Maximum	1.2	(Blank *et al.* 2007)
Thunnus albacares	Yellowfin tuna	Thunniform	32.1	7.212	Burst	5.1	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	32.1	7.212	Burst	2.7	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	52	7.212	Burst	5.5	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	62.1	7.212	Burst	6.9	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	66.5	7.212	Burst	20.7	(Sambilay 1990)

Thunnus albacares	Yellowfin tuna	Thunniform	66.5	7.212	Burst	12.5	(Sambilay 1990)
Thunnus albacares	Yellowfin tuna	Thunniform	62	7.212	Burst	5.2	(Sambilay 1990)
Thunnus orientalis	Pacific bluefin tuna	Thunniform	74	6.39*	Maximum	1.3	(Blank *et al.* 2007)
Thunnus thynnus	Atlantic bluefin tuna	Thunniform	0	5.535	Burst	1.5	(Block *et al.* 1992)
Trachurus japonicus	Jack mackerel	carangiform	18.2	2.34*	Maximum	2.4	(Riyanto *et al.* 2014)
Trachurus mediterraneus	Mediterranean horse mackerel	Carangiform	16	3.656	Burst	2.8	(Sambilay 1990)
Trigla spp.	Gurnard	subcarangiform	18	1.4*	Maximum	1.4	(Blaxter and Dickson 1959)
Xiphias gladius	Swordfish	Thunniform	0	5.813	Burst	2.3	(Block *et al.* 1992)
Xiphias gladius	Swordfish	Thunniform	220	5.813	Burst	25.0	(Sambilay 1990)

CHAPTER 6: Potential visual acuity and maximum swimming speed as predictors of trawl catch rates when using light as a bycatch reduction device in North-Eastern Tasmania

6.1. Introduction

In commercial fisheries, bycatch species (i.e. unwanted or illegal catch (DAFF 2000)) are vulnerable to the fishing gears that they interact with. Although commercial fishers are required to return these fish to the sea many suffer predation mortality or die as a result of injury or handling (Alverson *et al.* 1994). Within the Northern Prawn Fishery, for example, there can be as many as 350 species of teleost and elasmobranchs caught, many of which are unlikely to survive being discarded (Stobutzki *et al.* 2001). Despite the possible impact that commercial fisheries have on bycatch populations, bycatch species are often the lesser-studied in relation to understanding fish behaviour, morphology, and physiology. For this reason, this thesis has not only investigated the effect of a novel artificial light bycatch reduction device (BRD) on the catch rates of bycatch species themselves but also the morphological factors (i.e. visual capacity and swimming ability) that influence their catch rates.

So far, in this thesis the use of artificial light as a bycatch reduction device has been tested in terms of its influence on the catch rates of teleost species in temperate waters. It has been established that light can cause an overall decrease in the capture of some fish species in temperate waters. It was also found that the effect of light varies from species to species. Since there are differences in catch rates among species, it can be postulated that the variation is caused by the physiology or behaviour of a species. As mentioned by Clarke *et al.* (1986); Gordon *et al.* (2002); Hannah *et al.* (2015); Walsh and Hickey (1993), the differences in fishes (in terms of morphological, physiological, and behavioural) should be further studied to explain variation in catch rates.

Previously in this thesis, Chapters 4 and 5 have quantified various factors of visual capacity and swimming ability. Visual capacity was calculated in the form of potential visual acuity, defined as the fishes' ability to distinguish fine detail (Douglas and Djamgoz 1990). The swimming ability was expressed as the maximum swimming speed and represented the fastest theoretical speed of the fish based on the muscle twitch and distance covered in one tail beat. In this chapter, these morphological features will be used to compare and correlate with the catch data to see how each component may influence the catch rates of the fish species. This has not been attempted before. In theory, with the use of this model, the effect of light on a particular species

of interest can be estimated, provided there is information available on the fish species vision and swimming speed. The benefit of this model is that with the development of the light BRD into a commercial viable product, the model can predict the effect on the species composition without the need to undertake expensive and time consuming trawling (or fisheries) experiments.

This aim of this chapter, therefore, was to determine the relationships between teleost vision, maximum swimming speed, and the change in catch rates of North-Eastern Tasmanian fish species when using artificial light. Specifically, the model examined which factor had the greatest influence on catch rates and whether the model could be developed to predict the catch rates of other species in different international fisheries.

6.2. Method and materials

6.2.1. Data collection

As per the previous chapters, there were eight bycatch species of interest. The species were: sand flathead (*Platycephalus bassensis*), jack mackerel (*Trachurus declivis*), Degen's leatherjacket (*Thamnaconus degeni*), silver biddy (*Parequula melbournensis*), roundsnout gurnard (*Lepidotrigla mulhalli*), tiger flathead (*Neoplatycephalus richardsonii*), crested flounder (*Lophonectes gallus*) and eastern school whiting (*Sillago flindersi*).

The three variables used in this chapter to develop a model for predicting the catch rates of fish using a light BRD included: potential visual acuity, maximum swimming speed, and the difference in catch rates of species with and without the use of the light BRD. The mean potential visual acuity of each fish was estimated from histological processing of the eye (see Chapter 4 for full description of methods). The maximum swimming speed was estimated from a swimming speed formula that took into account stride length; muscle contraction and fish length (see Chapter 5 for full description of methods). The catch rates for each of these species was also used from the light BRD experiment (see Chapter 3 for full description of methods).

6.2.2. Data analysis

6.2.2.1. Swimming speed versus catch model

The swimming speed data was used to assess the relationship between swimming speed and the change in catch with the use of the light BRD. The maximum swimming speeds (m s^{-1}) for each of the key species of interest were plotted against the percent change in catch for catch per unit area (CPUA) in terms of weight (kg/km^2) and abundance (numbers/km^2). Since there were no observed maximum swimming speed estimates for *N. richardsoni*, *L. gallus*, and *S. flindersi*, they have been excluded from the analysis. A linear trendline was fitted to the data using the least squares approach and the trendline formula is provided. The correlation coefficient (R^2) is used to indicate the strength of the effect of maximum swimming speed on the precent change in catch.

6.2.2.2. Potential visual acuity versus catch model

The vision data was used to assess the relationship between potential visual acuity and the change in catch with the use of the light BRD. The potential visual acuity for the eight key species was plotted against the percentage change in catch for both WPUA(kg/km^2) and NPUA (number/km^2). A linear trendline was fitted to the data and the formula is provided. The R^2 is used to indicate the strength of the effect of potential visual acuity on the percent change in catch.

6.2.2.3. Final Euclidean model

The effect of both swimming speed and potential visual acuity was determined on the change in catch with the use of the light BRD. Using a criteria system each fish received a criteria value for the categories of speed and potential visual acuity, Table 1.

Table 1: Criteria values for speed and potential visual acuity categories.

Criteria value	Speed criteria	VA criteria
1	0-1 m/s	0-0.1
2	1-2 m/s	0.1-0.2
3	2-3 m/s	0.2-0.3
4	3-4 m/s	0.3-0.4
5	4-5 m/s	0.4-0.5
6	5+ m/s	0.5 +

Once each species was assigned a criteria value for each category, these were combined to form one value (β) using the Euclidean approach similar to that used in risk assessment (Nelson 2011). The final value utilises the Euclidean distance of speed and potential visual acuity with the following equation:

$$\beta = \sqrt{(S^2 + V^2)}$$

Where, β is the final Euclidean value produced; S is the swimming speed criteria value for each species; and V is the potential visual acuity criteria value for each species. The final Euclidean value (β) is plotted against the percent change in catch for both WPUA (kg/km^2) and NPUA (numbers/km^2). Linear trendlines were fitted the data and the linear relationship determined. The R^2 was used as an indicator of the effect of both potential visual acuity and swimming speed on the change in catch rates of species when using the light BRD.

For all data analyses, regression analyses were performed with statistical package 'R' (version 2.15.3). Significance level (α) was set at 0.05.

6.2.3. Application of the model

6.2.3.1. Use of light in the Northern Prawn Fishery

The effect of artificial light on species in the Northern Prawn Fishery was examined using the model presented in this chapter. The full list of teleost bycatch species that may be caught in the

NPF was gathered from Maynard and Gaston (2010) and Stobutzki *et al.* (2001). Although the exact potential visual acuity and maximum swimming speed data is not available for each one of these species, the approximate swimming speeds could be found using the average maximum swimming speeds of fish given the swimming mode they are classified into including: anguilliform, subcarangiform, carangiform, and thunniform. Since the weight contribution of each family is not equal, inferences were made based on the swimming modes of the families that accounted highest proportion of the total catch weight.

6.2.3.2. Comparison to other studies

The correlation seen between the swimming and visual abililty of a species and the change in catch with the use of artificial light is considered in another study. Hannah *et al.* (2015) has also observed the effect of artificial light on prawn and some fish species in a prawn trawl fishery in Oregon, US. The percentage change in catch reported by Hannah *et al.* (2015) was compared to the information available on potential visual acuity and maximum swimming speed which has been predicted using the formula established in Chapter 5.

6.3. Results

6.3.1. Criteria

Using the estimates of potential visual acuity and observed maximum swimming speed for the eight species of interest, the criteria values were allocated (Table 2). The influence of the potential visual acuity and swimming speed criteria on the final catch criteria is shown in Figure 1, whereby increasing visual (y-axis) and swimming (x-axis) criteria values increase the likelihood of escape (indicated by the grey arrow).

Table 2: The observed maximum speed and potential visual acuity of the eight fish species of interest and the associated criteria scores.

Species	Observed speed (m/s)	Criteria	VA	Criteria
T. degeni	3.20	4	0.1598	2
L. gallus	N/A	N/A	0.0775	1
L. mulhalli	1.72	2	0.1279	2
P. melbournensis	4.17	5	0.3138	4
T. declivis	6.42	6	0.1653	2
S. flindersi	N/A	N/A	0.1391	2
P. bassensis	4.83	5	0.1745	2
P. richardsonii	N/A	N/A	0.1658	2

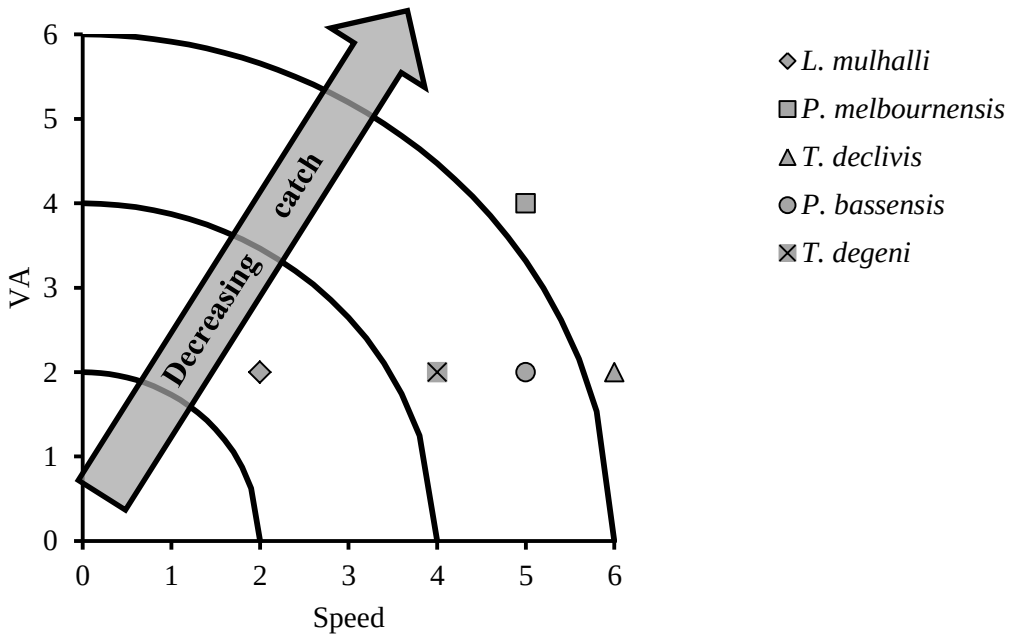

Figure 1: The criteria for VA and speed for each of the five species with the contour lines indicating the levels of likely catch rates. Following the direction of the arrow indicates the decreased levels of catch.

6.3.2. Swimming speed versus catch model

There was a strong negative relationship between maximum swimming speed (m s^{-1}) and the percent change in catch for both WPUA (kg/km^2) (F= 14.29, df= 1, 3, p= 0.03) and NPUA (number/km^2) (F= 22.71, df= 1, 3, p= 0.02). With the increasing maximum swimming speed of the species there was a greater decrease in catch (Figures 2 and 3). Maximum swimming speed accounted for 83 % of the change in catch weight and 88 % of the change in catch numbers. The species with the greatest maximum swimming speed of 6.4 m s^{-1} had the greatest decrease in catch for both weight and numbers.

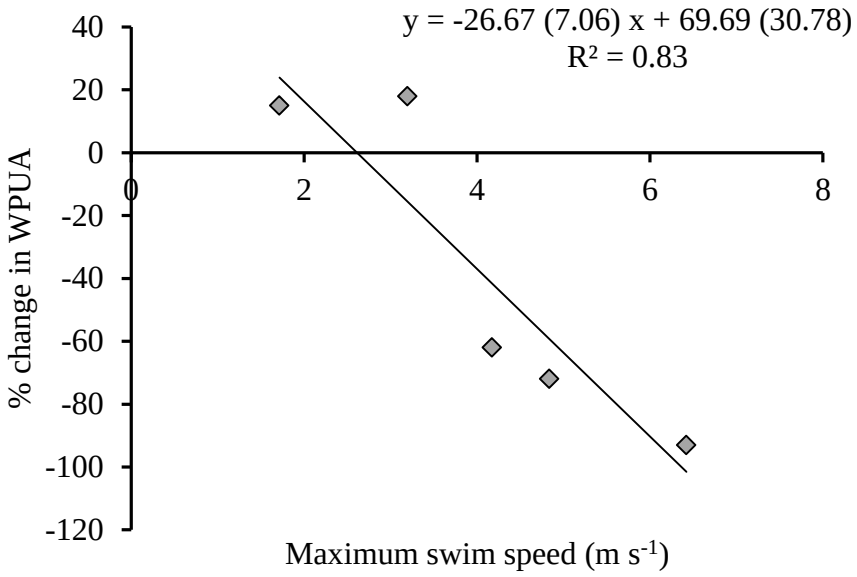

Figure 2: The percentage change in WPUA (kg/km^2) plotted against the observed maximum swimming speed (m s^{-1}) of the five fish species with the linear relationship and R^2. Values in brackets are standard error.

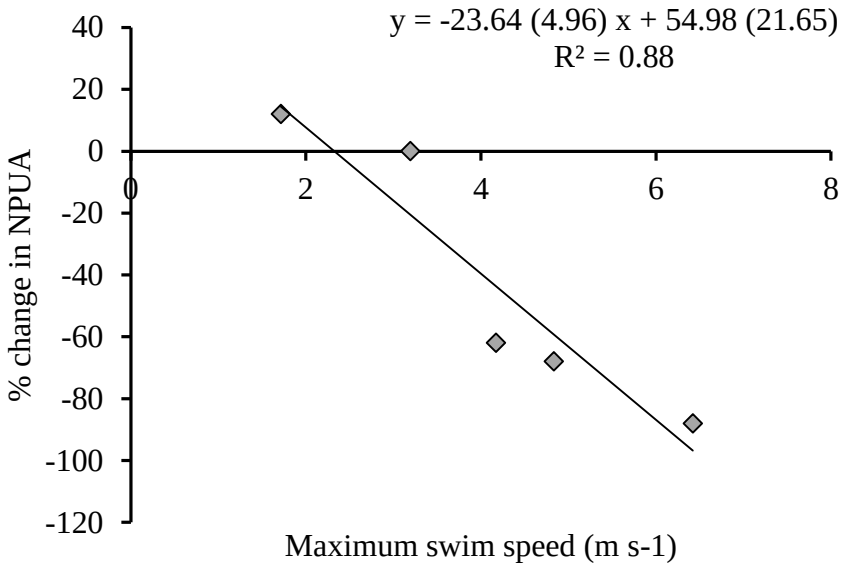

Figure 3: The percentage change in NPUA (number/km^2) plotted against the observed maximum swimming speed (m s^{-1}) of the five finfih specieswith the linear relationship and R^2. Values in brackets are standard error.

6.3.3. Potential visual acuity versus catch model

There was a non-significant negative relationship between potential visual acuity and the percent change in catch for both WPUA (kg/km^2) (F= 1.81, df= 1, 6, p= 0.23) and NPUA (number/km^2) (F= 0.34, df= 1, 6, p= 0.58) (Figure 4 and Figure 5). The change in potential visual acuity only accounted for 23 % of the change in catch numbers and 5 % of the change in catch weight.

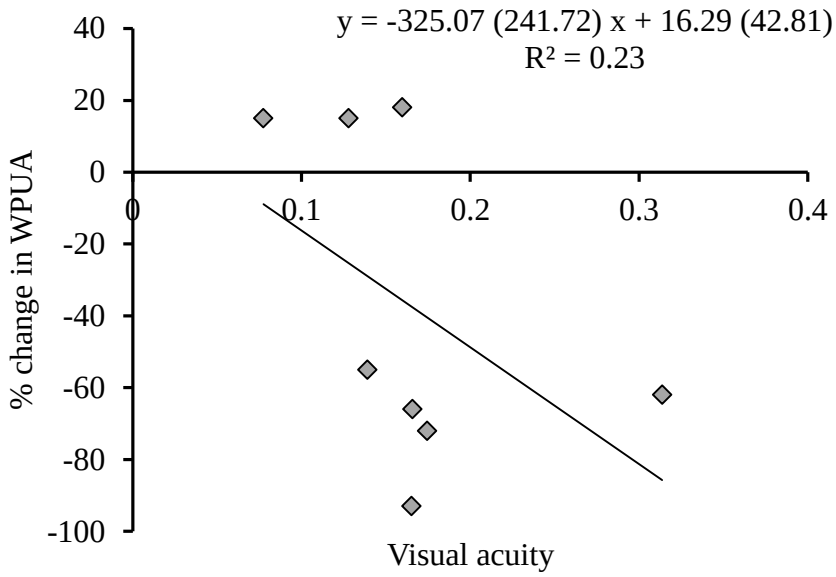

Figure 4: The percentage change in WPUA (kg/km^2) plotted against the potential visual acuity with the linear relationship and R^2. Values in brackets are standard error.

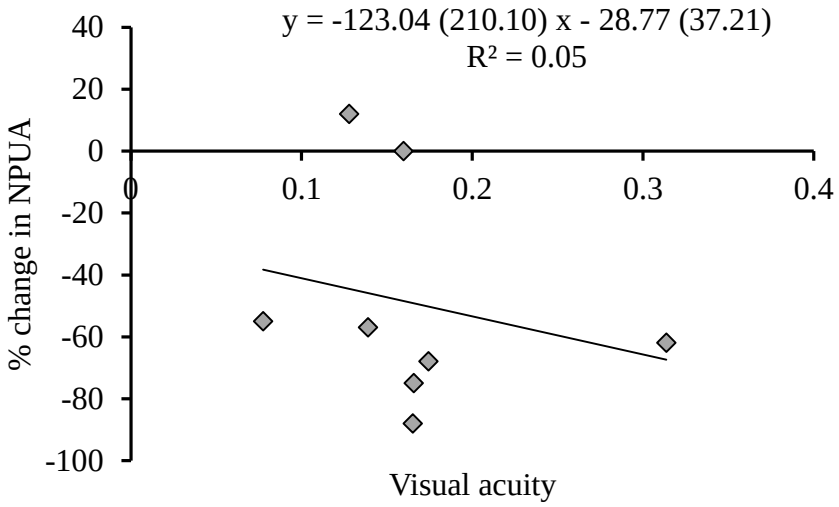

Figure 5: The percentage change in NPUA (number/km^2) plotted against the potential visual acuity with the linear relationship and R^2. Values in brackets are standard error.

6.3.4. Final Euclidean model

The final Euclidean values (β) for the eight species ranged from 2.8 for *L. mulhalli* to 6.4 for *P. melbournensis* (Table 3). As there were no estimated maximum speed for *L. gallus*, *N. richardsoni*, and *S. flindersi* they did not have final Euclidean values and were excluded from the analysis.

Table 3: The criteria for maximum swimming speed and potential visual acuity and the final Euclidean value (β) for each species of the eight key species.

Species	Max speed	Criteria	VA	Criteria	β
L. gallus	N/A	N/A	0.08	1	N/A
L. mulhalli	1.7	2	0.13	2	2.8
N. richardsoni	N/A	N/A	0.17	2	N/A
P. bassensis	4.8	5	0.17	2	5.4
P. melbournensis	4.2	5	0.31	4	6.4
S. flindersi	N/A	N/A	0.14	2	N/A
T. declivis	6.4	6	0.17	2	6.3
T. degeni	3.2	4	0.16	2	4.5

There was a nonsignificant negative relationships between the final Euclidean values (β) and the percent change in catch for WPUA (kg/km^2) (F= 8.42, df= 1, 3, p= 0.06) (Figure 6). There was, however a significant strong negative relationship between the final Euclidean values (β) and the percent change in catch for NPUA (number/km^2) (F= 13.70, df= 1, 3, p= 0.03) (Figure 7). The Euclidean value accounted for 74 % of the change in catch weight and 82 % of the change in catch number. The greater the Euclidean value for a species the greater the decrease in catch with the use of a light BRD.

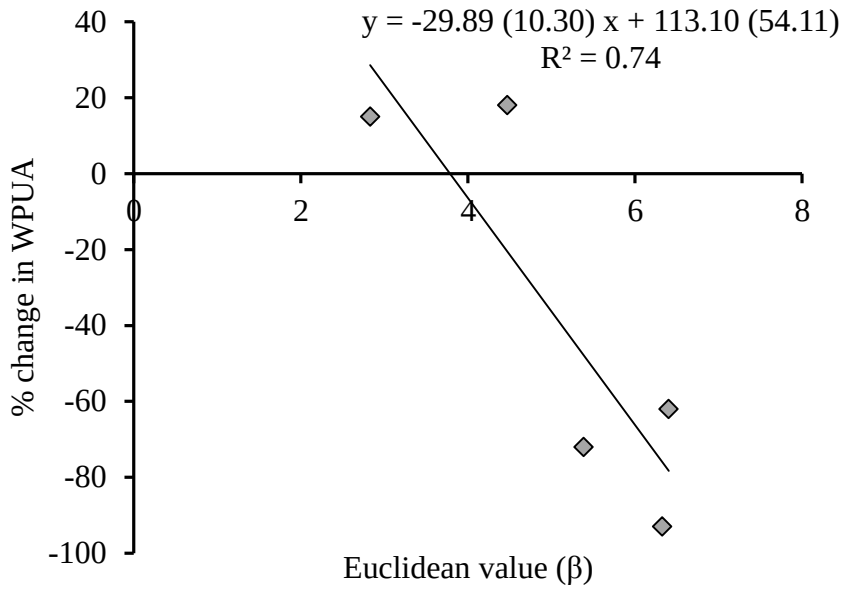

Figure 6: The percentage change in WPUA (kg/km^2) plotted against the final Euclidean value (β) with the linear relationship and R^2. Values in brackets are standard error.

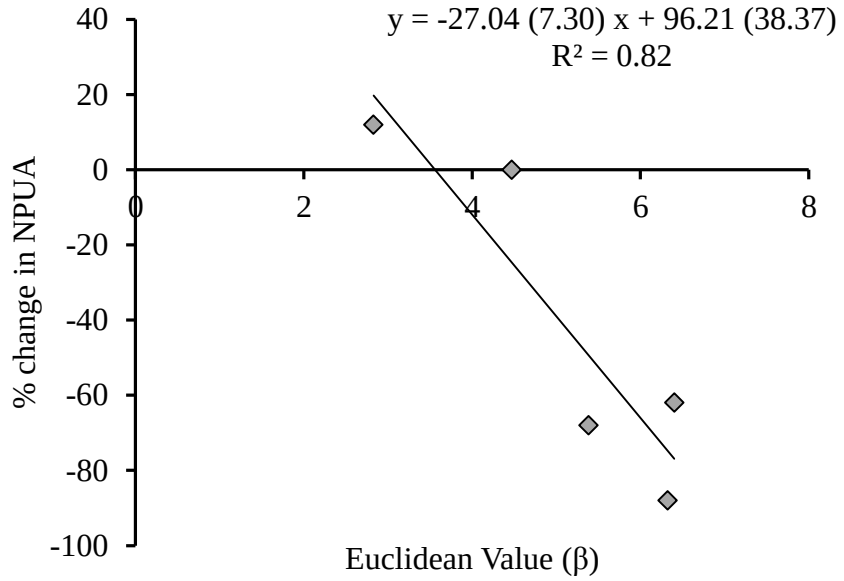

Figure 7: The percentage change in NPUA (number/km^2) plotted against the final Euclidean value (β) with the linear relationship and R^2. Values in brackets are standard error.

6.3.5. Application of the models

6.3.5.1. Use of light in the Northern Prawn Fishery

Using a list of all the possible teleost bycatch species gathered from Maynard and Gaston (2010) and Stobutzki *et al.* (2001) there were 84 families that might be encountered in the tropical waters of Australia's Northern coast. Out of these families, there were 9 families that accounted for most (80%) of the catch in terms of weight (Figure 8).

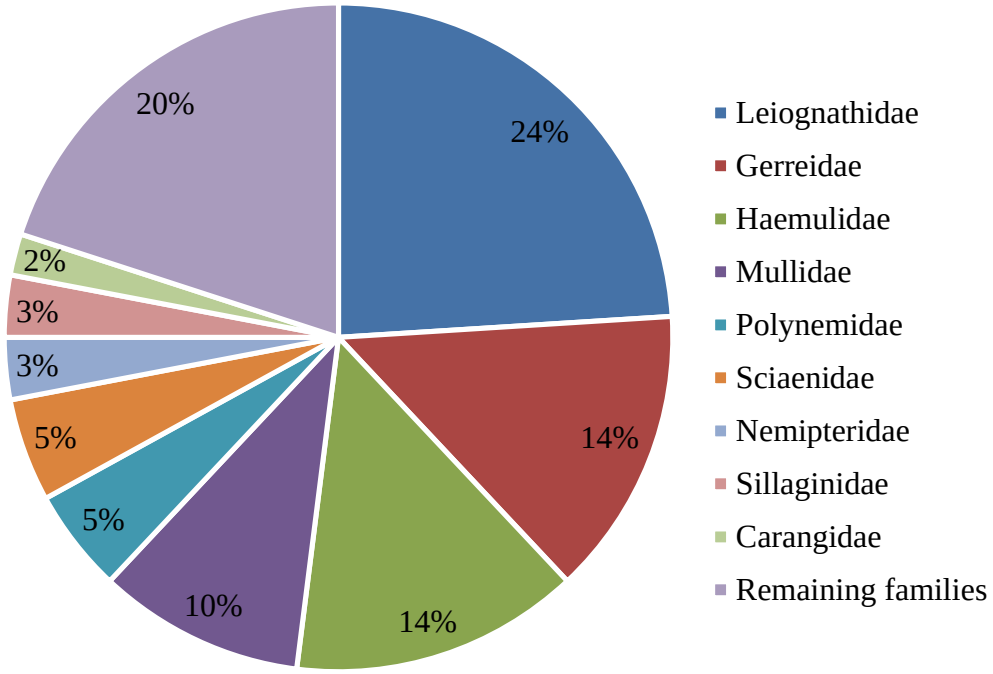

Figure 8: Pie chart representing the percentage of the top 9 families that could be potentially caught in the Northern Prawn Fishery (based on list of species in (Maynard and Gaston (2010); Stobutzki *et al.* (2001)).

In this chapter, it was found that the swimming speed had a stronger influence on the change in catch rates than the potential visual acuity of a species. Therefore, only maximum swimming speed was used as a predictor in this application of the model to the NPF. By classifying each species by its swimming mode, its approximate swimming speed was found. Based on the linear model presented in section 6.3.2 it was found that the minimum swimming speed required for catch to decrease was 2.6 m s^{-1}.

Nine of the species account for the 80 % of the catch weight, and of these it was found that 3 of the families were carangiform swimmers while the other 6 were subcarangiform swimmers (Figure 9).

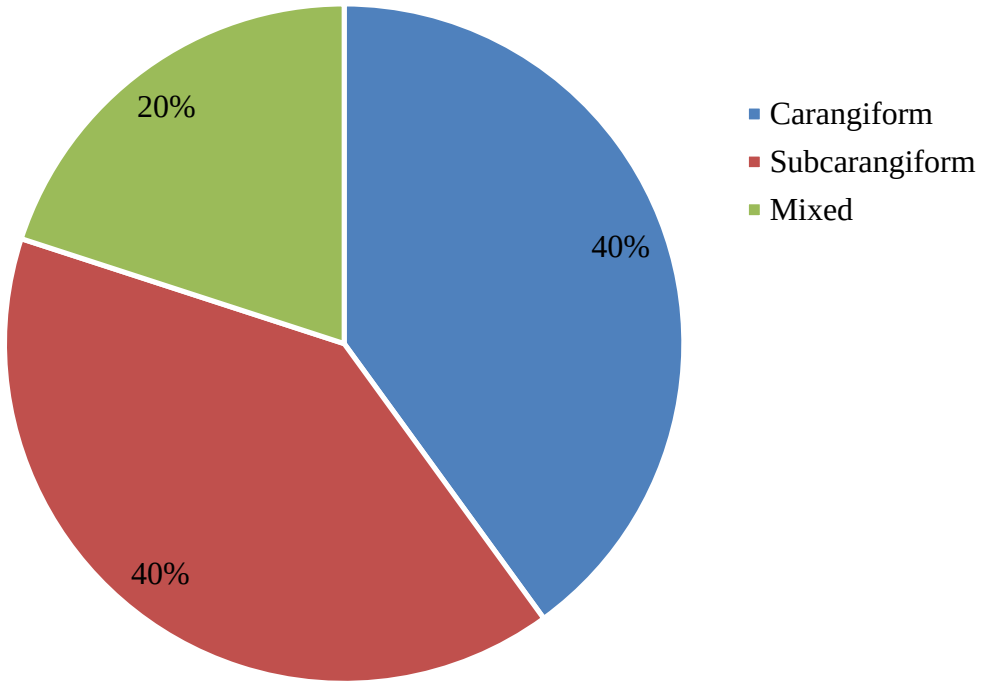

Figure 9: Pie chart representing the swimming modes of the top 9 species and the remaining 20 % of the catch. (using information from Maynard and Gaston (2010)).

6.3.5.2. Comparison to other studies

Using the three species presented in Hannah *et al.* (2015), the relationship between predicted maximum speed and change in catch was calculated. As per the previous section, only maximum swimming speed was used as it had the greatest effect on the change of catch rates when using artificial light. For the three species, eulachon (*Thaleichthys pacificus*), slender sole (*Lyopsetta exilis*), and darkblotched rockfish (*Sebastes crameri*), the maximum speed was calculated from their caudal fin aspect ratios using the maximum swimming speed formula from Chapter 5 (Section 5.3.2.3.). The linear relationship was described by $y = -110.4x + 27.104$. Due to the small sample size, a statistical analysis was not conducted. However, it can be seen that 78 % of the change in catch is due to the change in maximum swimming speed (Figure 9).

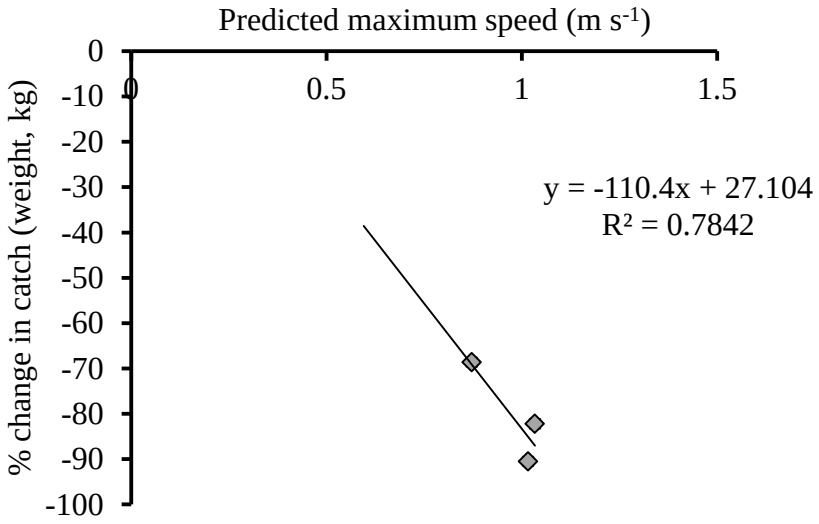

Figure 10: The percent change in catch (kg) and the predicted maximum swimming speed (m s^{-1}) plotted with the linear relationship and the R^2.

6.4. Discussion

The models developed in this chapter demonstrate ways of predicting the catch rates of a species; whether it increases or decreases with the use of light, and by how much. If the approximate speed of fish and potential visual acuity is known then the reaction of fish to the light BRD developed in this research can be estimated. This is beneficial for commercial fisheries that operate in various locations with different species of fish to predict the effectiveness of this novel device.

As discussed in previous chapters the development of a BRD that utilises light to reduce the capture of unwanted bycatch species could be beneficial to commercial prawn trawl fisheries. Since a light BRD can increase the visual warning in front of the net during night time trawling, it has been shown to decrease fish capture by half (Chapter 3). As well as the benefit of reducing the number of fish that are hauled to the back deck (and as such reducing sorting time, increasing target species (i.e. prawn) quality, and reducing impact on bycatch species populations) there is the added bonus of reducing the interaction between the gear and potential bycatch. It has been established that both maximum swimming speed and potential visual acuity are the dominant factors influencing the ability of a fish to detect and avoid trawl gear (Clarke *et al.* 1986; Jones *et al.* 2004). With the model developed in this chapter the effect of these two factors can be quantified.

6.4.1. Comparison of visual and swimming ability as predictors

In this chapter, when comparing the potential visual acuity and maximum swimming speed to the catch data, separately, it can be seen with the regression coefficient that the swimming speed has a strong relationship whereas potential visual acuity does not. The relationship between maximum swimming speed and percent change in catch had regression coefficients of 0.83 and 0.88 for weight and numbers, respectively. The relationship between potential visual acuity and percent change in catch had lower regression coefficients of 0.23 and 0.05 for weight and numbers, respectively. This means that maximum swimming speed accounts for more of the change in catch with the use of light than potential visual acuity. However, potential visual acuity still plays an important role in the detection of an oncoming trawl. In particular, it is the visual system that is able to detect the artificial light and potentially initiate a response where it

may not have otherwise. While it has been established that increasing visual capacity does not increase chances of escape, vision is still essential for that initial detection of an illuminated trawl. It is potential visual acuity that will allow fish to detect the finer details of a net, something that may be of use when trying to escape from within. However, in terms of increasing the visual warning of a trawl using light, it is assumed in this study that the fish engages in large scale avoidance.

By combining the two factors, swimming speed and potential visual acuity, with the Euclidean method, the resulting regression model is not as strong as the swimming speed model alone. With regression coefficients of 0.74 and 0.82 for weight and numbers, respectively, it can be seen that the inclusion of potential visual acuity has weakened the relationship with catch rates. It is therefore advised that maximum swimming speed is the most accurate method for predicting the catch rates of a fish species with the use of artificial light.

6.4.2. Application of the models

The Euclidean approach has been used for a variety of studies from Productivity-Susceptibility Analyses as a sort of risk analysis for habitats (eg. Katie *et al.* (2014); Patrick *et al.* (2010); Williams *et al.* (2011)) for the development of management tools (eg. Baez *et al.* (2007); Palmer *et al.* (2009); Yergey *et al.* (2012)). The use of this approach in commercial fisheries is usually to produce cluster trees to organise for example groups of trawls (i.e. Branch *et al.* (2005); Sbrana *et al.* (2003)). To the author's knowledge, no published studies have used this technique to directly compare the morphology and movement of fish to the catch rates within a trawl. Also, there have been no attempts to develop a model to predict the catch rates within a trawl that has been equipped with an artificial light BRD.

An ideal industry for the use of a light BRD would be a commercial prawn trawl fishery operating in the tropical waters of Northern Australia. In the Gulf of Carpentaria, for example, there has been as many as 84 families of teleost fishes captured in commercial prawn trawling as bycatch (Maynard and Gaston 2010; Stobutzki *et al.* 2001). Since maximum swimming speed appears the dominant factor influencing the possible reduction in catch, this chapter examines the application of the Euclidean model to predict the effectiveness of the light BRD in the Northern Prawn Fishery as a case study. Of the 84 families, there were nine families that accounted for 80

% of the total catch weight. Based on the potential maximum swimming speeds, it is likely that the three carangiforms that account for 40% of the catch (which include Leiognathidae, Gerreidae, and Carangidae), are most likely to avoid the trawl. The other six families which made up the other 40% (which include Haemulidae, Mullidae, Polynemidae, Sciaenidae, Nemipteridae, and Sillaginidae) may be able to swim fast enough to avoid the trawl. It can be seen that with maximum swimming speed as the most important characteristic depicting the likelihood of avoidance and at least half the catch will be positively benefited. It must be acknowledged that there is a high degree of variation acroos the Gulf the Carpentaria (as in many fisheries) and the species mix would change at any geographical location.

The application of the Euclidean model presented in this chapter was also further extended to examine the relationship between the change in catch and maximum swimming speed data from another study. Hannah et al. (2015) conducted a study on the effect of artificial light on prawn trawl nets in the small mesh trawl fishery operating off the coast of Oregon, US. They found that the use of light on the prawn trawl nets decreased the capture of the primary bycatch species eulachon (*Thaleichthys pacificus*) as well as two other species, slender sole (*Lyopsetta exilis*), and darkblotched rockfish (*Sebastes crameri*). In this chapter, it was found that there was a strong linear correlation between the predicted maximum swimming speed and the % change in catch for three species presented in Hannah *et al.* (2015). It was found that the maximum swimming speed of those three bycatch species had a strong effect on the catch rates in the presence of artificial light. Therefore, this supports the use of maximum swimming speed as a predictor of catch rates as well as demonstrates the effectiveness of light as a bycatch reduction device overseas.

6.4.3. Conclusion

This chapter found, with the data presented here, that maximum swimming speed has the strongest influence over the catch rates of species with the use of lights on trawl gear. The fastest species in the study, *T. declivis*, also had the greatest reduction in catch. By modelling this relationship, the effect of light on other species could be predicted. Although vision is required for the initial detection and reaction to the lights, it was found that by measuring how fast a fish can swim, the change in catch rates can be estimated from this model. This is beneficial for the development of the new BRD concept using light, because the effect of light on the bycatch

species of a particular fishery or location can be predicted. This study has filled a large knowledge gap that has been speculated for many years about the important relationship between swimming potential and the catch rates of a species with the use of artificial light.

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CHAPTER 7: General conclusions

7.1. Summary of findings

Seafood is an important source of protein and as of 2010, it accounted for 16.7 % of the world's animal protein (FAO 2014). There are also non-food uses for harvested seafood, such as pharmaceutical products, supplements, bait, jewellery and pet food (FAO 2014). However, discarding unwanted fish species is considered to be one of the greatest threats to the sustainability of commercial fisheries worldwide (Bellido *et al.* 2011; Davies *et al.* 2009). This wasteful practice is prominent in the commercial prawn industry worldwide and modifications to trawl gear and devices are continually being tested as a means for reducing the capture of unwanted fish species (aka 'bycatch') (DAFF 2000).

This current research followed the development and experimental testing of a novel bycatch reduction device that used artificial light to reduce the capture of fish species in a prawn trawl. Whilst there have been some studies that have conducted preliminary investigation into this concept (Clarke *et al.* 1986; Gordon *et al.* 2002; Hannah *et al.* 2015), none have explained the reasons why certain species of fish have an increased ability to avoid a trawl in the presence of moving light and as a consequence are caught in smaller numbers.

From the experimental trials of the newly developed light BRD, analysis of the catch revealed the overall effect on a species by species basis. By conducting the trials in Tasmanian coastal waters, the effect of using moving light on the eight species of interest studied in this thesis allowed for comparison between species. The results of the trials showed that overall the total catch of teleost species was halved. On a species by species basis, *T.declivis* had the greatest percentage reduction in both WPUA and NPUA . At the other end of the spectrum, *T. degeni* had the greatest percentage increase in WPUA and *L. mulhalli* had the greatest percentage increase in terms of NPUA . Unfortunately, the trials in the tropical Moreton Bay prawn trawl fishery were less successful due to some malfunctioning of the lights and it was hard to draw meaningful conclusions from the response of different species. The results of these experiments answered research question 1, which was to examine the effect of artificial light on standardised catch rates and species composition. It was in fact found that the increased visual warning (created by the artificial light) reduced the capture of fish bycatch. For most of the species caught, the light caused a reduction while for some it increased. There appears to be no real effect on size

composition of a species in terms of size range and mean size, which is surprising as larger individuals are considered as faster swimmers. In terms of the prototype design, within the scope of this research the ideal design was documented. A fully working set of lights, however, was not successfully produced within the time frame of this project.

The first step is explaining the response by separately investigating the visual and swimming capacity of fish. Of the eight species of interest, *L. gallus* had the lowest potential visual acuity (0.08) and *P. melbournensis* had the highest (0.31). It was also seen that *L. mulhalli* had the lowest density of rods and *T. declivis* had the greatest and that all the species except *T. declivis*, had a regular square cone mosaic. Based on retinal morphology and calculated potential visual acuity, *T. declivis* (high rod density) and *P. melbournensis* (high cone density, high potential visual acuity, and large relative eye size) were the species in this study most likely to react to lights used on fishing gear. This answered research question 2, which was to examine the physiology of the eyes of eight commonly caught species in North-Eastern Tasmania. This includes quantifying the densities of photoreceptor cells (rods and cones) as well as estimating the potential visual acuities of each species. It was found that the density of rods increased significantly with increasing depth. Since rods are responsible for detecting dim light, they are the dominant photoreceptor in the retinas of fish that live in deeper water. It was also found in this study that the densities of photoreceptor cells as well as the potential visual acuity were different between the eight morphologically different species.

Based on the swimming speed experiments conducted, it was found that of the eight species studied, *T. declivis* had the greatest maximum speed. On the other hand, *L. muhalli* was the slowest species observed in this study. Using historical swimming speed data in the literature from 1957 until the present day, a correlation was found between the maximum swimming speed and the morphometrics of the fish. These results suggest that by knowing the swimming mode (i.e. anguilliform, subcarangiform, carangiform, or thunniform), an approximate speed of the species can be calculated. From this, it was found that thunniform species are the fastest swimming fish. This answered research question 3, which was to investigate the maximum swimming speed of the same eight fish species defined as the burst swimming speed. There appears to be a correlation between the swimming mode and maximum speed of fish. The shape and swimming style of fish can be categorized into Anguilliform, Subcarangiform, Carangiform

and Thunniform. This study found that each of these have different maximum swimming speeds. Following on from the examination of swimming modes, it was found that the morphometric measurement of caudal fin aspect ratio can be used to predict the maximum swimming speed of any species. It was found that there was slight variation in maximum speed with the different size of increase (within a species).

The effect of fish morphology on the ability to escape a trawl can be found by correlating the vision and swimming speed with the percent change in catch with the use of light. A final criteria value was found to correlate significantly with the percent change in WPUA and NPUA. However, swimming speed on its own has a stronger relationship. This means that the faster the fish, the more likely it will escape a trawl aided by artificial light, as was the case with *T. declivis* which was the fastest species and had the largest percent reduction in WPUA and NPUA. So, potential visual acuity appears to be most important for the initial detection of the light. This answers the research question 4, which was to find the relationship between the visual capability and catch rates as well as the swimming capability and catch rates. The purpose of this was to see if there was a way to predict the effect of artificial light on species caught in a prawn trawl net. It was found that maximum swimming speed and not potential visual acuity had an effect on the change of catch when using an artificial light. Maximum swimming speed accounted for up to 88 % of the change in catch. It was concluded that once the visual system has been stimulated, maximum swimming speed alone could be used to predict the effect of artificial light on species, in terms of change in catch.

It must be acknowledged that there are some limitations to the applicability of this research. For instance, whilst the lights system was only tested successfully in Tasmania, the only location tested as a representative of the commercial prawn trawl industry was Moreton Bay, Queensland. It is not known that the effect of this novel system on other species in other locations will have identical results. Similarly, the biological data collected on the eight species of interest in this research can only be applied to these species. There can be variation even between similar species in terms of photoreceptor densities and maximum swimming speed.

7.2. Implications of this research

As suggested by Clarke *et al.* (1986); Gordon *et al.* (2002); and Hannah *et al.* (2015), the knowledge of the differences among the fish (in terms of morphology, behaviour and physiology) should be studied to explain the differences in the catch when using a light BRD. This research is the first of its kind to bring together the catch data from testing a new BRD and linking it to the morphology of the fish in an attempt to explain the differences in the results. This type of research, that merges biological descriptions of species with the catch data from BRD experiments could change the way that experiments are conducted. Instead of just looking at the effect of a device or modification to this gear has on catch rates, biological predictors can be examined and used to predict future effects on species.

This research allows for predictions to be made on the likelihood of percent change in catch rates with the use of this novel device. It was shown that the maximum swim speed of a species can be used to predict the change in catch with the use of artificial light. This is beneficial because it could be very time consuming and costly to run experiments on fish each time this device is introduced to a new area. For example, it is very expensive to charter vessels and spend time at sea, as well as any reimbursements that may be required if the experiment imposes on regular commercial operations. Instead, in this study, the approximate impact of moving light can be established based on the knowledge of how a fish swims which will save time and money.

Finally, and most importantly, this study demonstrates the effect of light on the capture of fish bycatch species. This substantially has many benefits for the commercial prawn trawl industry including: reduced sorting times; increased quality of prawns; reduced drag which leads to more efficient fuel use; and reduced impact on fish bycatch populations. To implement such a novel device into industry, it must meet certain criteria. From the fishers perspective, cost reductions and increased quality of catch are often priorities. However, from the perspective of government and society it is paramount to always be moving towards more sustainable fishing, which can be achieved when the impact on bycatch populations is reduced.

7.3. Where to from here?

This research has provided the basis for combining an understanding of the morphology and the catch rate of a particular species when testing a light BRD. From here, it is recommended that different light intensities are tested to *a*) establish the ideal light intensity that provides an optimum trade-off between reduction in catch and the battery power required to and *b*) to observe if the percent change in catch rates of a certain species correlates with the amount of light used. The use of different wavelengths could also be tested for particular fisheries with a range of species compositions. It is understood that different species are capable of detecting different wavelengths of light, depending on their habitat. Species could experience different catch rates if the wavelength of the light used for the BRD was altered..

During the course of this research, there was insufficient time to finish developing a commercially viable BRD design that would withstand the impact of the weather and commercial fishing gear. Some design characteristics were trialled and some failed. The study found that simplicity is the best approach and that there is not one design that will suit every fishery. These trials provide an important design template, to inform any future endeavours to produce a marketable LED device.

The completion of a commercially viable prototype would need to go through the rigours of BRD protocol testing (SAFMC 1997). This includes passing the three assessment stages: initial; visual; and at-sea assessment and could take some refinement along the way. As part of this, stakeholder engagement is crucial for the uptake of a new device (Gullet 2003) and as such a workshop with stakeholders should be held. The purpose of such a workshop would be to disclose the potential success of this novel device as well as how to operate, the costs, maintainence and future developments. It is possible that with fishermen committed to the investment, a device of this nature could be operational in many commercial prawn trawl fisheries.

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